University of Southern Queensland
Faculty of Engineering and Surveying

Hydraulic properties of Toowoomba soils for laundry water reuse

A dissertation submitted by

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Abstract

The main purpose of this project was to evaluate the potential effects of laundry water irrigation of residential lawns and gardens on the soil hydraulic properties. The project aimed to experimentally determine the soil properties such as pH, EC, soil water retention and saturated hydraulic conductivity using a typical soil in the Toowoomba city.

A set of three treatments were used for various experiments. Undisturbed soil cores (referred to as field cores) were used as a treatment to simulate the application of laundry water on well established gardens of suburban backyards. Furthermore, disturbed soil cores referred to as loose and compacted treatments were used to simulate the application of laundry water on recently prepared garden beds and somewhat older garden beds (with some settlement), respectively. Experiments involved two leaching scenarios in which laundry water was applied to initially moist (unsaturated) soils and to wet (saturated) soils.

Results show that compacted soils retained significantly more water at high suction and field capacity than loose or field soils. Values of saturated hydraulic conductivity (K_{sat}) for most treatments were fond to decrease by an average of 90% when laundry water was used to infiltrate the moist soil. When laundry water was used to infiltrate into the saturated soils, the values of K_{sat} were reduced by 80 ± 6%. In addition, a further reduction of 61 ± 8% was resulted when laundry water irrigation was followed with tap water. In contrast, the drainage from laundry water had similar properties to the drainage using tap water.

Due to apparent purification of the laundry water during drainage, the risk of ground water contamination from salts is reduced, but the potential for soil to accumulate salt and degradation is increased.

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List of Abbreviations

ANZECC	Australian & New Zealand Environmental & Conservation Council
AWRC	Australian Water Resource Council
BD	Bulk density in g/cm3
CEC	Cation exchange capacity in meq./100g of soil
cfu/100 ml	Colony forming units per 100 ml
CSIRO	Commonwealth Scientific and Industrial Research
DDL	Diffused Double Layer
EPA	Environmental Protection Agency
EC	Electrical conductivity in µS/cm (1000µS/cm = 1dS/m)
ESP	Exchangeable sodium percentage
K	Hydraulic conductivity in mm/h
Ksat	Saturated hydraulic conductivity in mm/h
LW	Laundry water
pH	logarithm of hydrogen ion activity in water or soil solution
PL	Plastic limit
SAR	Sodium adsorption ratio
TW	Tap water
WADH	Western Australia Department of Health
WCg	Gravimetric moisture content
WCv	Volumetric moisture content

Glossary of Terms

Absorption (chemistry) The process by which one substance is taken up by another substance.

Buffering The process that constrain the shift in pH when acids or bases are added. More generally, processes that constrain shifts in the dissolved concentration of any ion when it is added to or removed from the system.

Capillarity Forces between water and soil surfaces in the small (capillary) pores

Electrical Conductivity (EC) The reciprocal of electrical resistivity, the conductivity of electricity through water or an extract of soil; expressed in decisiemens or siemens per meter (dS/m) at 25ºC. It is a measure of soluble salt content in solution.

Exchangeable Sodium Percentage (ESP) (of sol) Amount of exchangeable Na expressed as a percentage of total exchangeable cations.

Hydraulic Conductivity (K) The rate at which water passes through a soil material under unit gradient

Pore size distribution The volume fraction of the various sizes of pores in a soil.

Porosity The volume percentage of the total bulk density of soil not occupied by solid particles. The volume of pores in a sample divided by the sample volume.

Potential gradient. The rate of change of potential with distance. The driving force of water through a medium.

Saturated Generally, occupying all of a capacity. With respect to water, the condition of a soil when all pores are filled with water.

Sodium adsorption ratio(SAR) The relationship of soluble sodium to soluble calcium plus magnesium in water or the soil solution, expressed by the equation: SAR = [sodium]/[calcium + magnesium]1/2, where the concentration of ions, denoted by square brackets, are in millimoles per litre.

Soil core A volume of soil obtained by forcing a cylindrical device into the ground (eg soil, sediment), usually perpendicular to the horizontal.

Soil order In sol classification, the most general level of classification where all soils fit into 12 orders.

Soil solution The liquid phase of the soil and its solutes.

Soil structure (pedology) The combination or arrangement of primary soil particles into secondary units or peds. The units are characterized and classified on the basis of size, shape, and degree of distinctness.

Soil texture The relative proportion of the various soil separates-sand, silt and clay-that make up the soil texture classes as described by the textural triangle.

Soil bulk density The dry mass (weight) of soil per unit bulk volume.

Water potential The tendency of sol water to move; the sum of gravity, pressure, matric, and solute components.

Water retention curve or soil-water characteristic curve The graphical relationship between soil water content and the soil-water matric potential (the energy required to removed the water).

Chapter 1

Introduction

1.1 Background

Average rainfall over the Australian continent is low in comparison with other continents. Australia receives an average rainfall of 420 mm per year, where its effect is compounded by its variability and the high rate of evaporation. Australia has an average evaporation of 1,800 mm/year, making it the one of the world driest continents (Smith et al. 1983). Therefore, Australia has experienced a series of droughts those affect the livelihoods of its population. On the other hand, Australia is the world second largest user of domestic water per capita after the United State of America (Hutcheon 2005).

Water resource and water use related issues have been recognised as one of the important social, economical and environmental issues challenging Australia. Rapid growth in the demand for high quality water coupled with natural shortage and continuous restrictions in supply have accelerated the search for alternative sources. Many communities and city councils in Australia have adopted water conservation and reuse practices. The Toowoomba City Council (TCC) has enforced water restriction policy due to the current and future potential shortage of water supply. Increasing population and drought have contributed to the city's dwindling water supplies. The city reservoirs need at least 500 mm of rain in a short time over the dam catchment areas to overcome recent water shortage. The water level in the city's main reservoir is at about 30% of its capacity, pressuring the TCC to work on a water demand management strategy. TCC is aware of the reuse options for treated wastewater on public recreation areas such as golf-courses and lawns. In general, greywater can be reused through three options. The first option is the centralised treatment of wastewater that is piped back to the individual households for reuse. The second option is the adoption of onsite treatment and reuse system. Lastly, the greywater such as laundry water can be used directly without any treatment

(SECITARC 2002). The potential reuse of domestic greywater, particularly the direct reuse of domestic laundry water has been investigated through the TCC environmental sections. This direct reuse option may be feasible if practiced under regulations to reduce human and environmental health risks (Brennan and Patterson 2004).

1.2 Reuse of Reclaimed Water

Wastewater has been applied to crops, rangelands, forests, parks and golf courses in many parts of the world (Steward et al. 1986; Angelakis et al. 1999; Al-Jamal et al. 2002). Furthermore, Harruvy (1996) and Frieddler (2001) indicated that Israel uses more than 65% of the country's wastewater for irrigation.

Irrigation of lawns and gardens has great potential for small scale reuse of reclaimed greywater. Using laundry water and other greywater for on-site irrigation of ornamental plants not only reduces the volume of wastewater that must be disposed of through septic systems, but also saves potable water currently used for irrigation (Amoozegar et al. 2004). The average household potable water usage could be reduced by between 30-50 % if the domestic greywater could be reused (Jeppesen, 1996). However, potential health risks are associated with the direct contact and accidental exposure to the reclaimed water such as exposure to aerosols generated by spray irrigation. The major health risk is infection from micro-organisms which is indicated by the presence of thermotolerant coliforms or *E. coli* (EPA and DOH 1999).

According to Capra and Scicolone (2004), drip irrigation is particularly suitable for wastewater reuse because it minimises the health risks to farmers and product consumers due to reduced exposure and contact with the wastewater. The performance of drip irrigation for wastewater reuse is mainly limited by the clogging of emitters. Drip irrigation system prevents the formation of aerosols while runoff and deep percolation are negligible. Due to the health risk associated with the use of greywater, the current recommendation is to irrigate soils with greywater by the sub-surface methods. Jeppesen (1996) indicated that sub-surface irrigation of greywater

is arguably the safest, most efficient and effective method of lawn and garden watering when applied in a zone of 200 mm to 300 mm below the surface. Most pathogens are less likely to survive if greywater is applied in this zone because this zone is the most aerobic and dominated by high natural microbial activity. Greywater has some nutrients that may be valuable as fertilisers for lawns and gardens. The nutrients contained in greywater namely nitrogen, phosphorous, potassium and sulphur would benefit plants providing that they are in moderate concentrations (Sharman 1993). However, other chemicals presenting in greywater may be harmful to soils and vegetation. Sodium, total salts, chloride and boron present in greywater could negatively impact the environmental health of soils and plants (Fisher 1988).

Therefore, the human and environmental health risks associated with the reuse of grey water are of major concerns. This type of reuse has been an issue that requires further scientific evaluation and technological development to support such schemes. Guidelines and regulations for the reuse of greywater are published to advise and raise the public awareness on potential health risks. Even though, the benefits of grey water reuse are well documented and published, little has been done on examining its effects on the soils' physical and chemical properties.

1.3 The Potential of Laundry Water for Reuse

Laundry water is a component of greywater and contributes to about one third of the total grey water volume. Therefore, it has a good irrigation potential due to its quantity and better quality (less contamination) compared to those of the greywater generated from kitchen and bath room (EPA and DOH 1999).

On the other hand, some chemicals present in laundry water, especially sodium could adversely affect the stability and hydraulic properties of soils that continually receive laundry water. Soil affects plant growth by providing plant support, nutrients, water requirement and aeration (Brady and Weil 1999). Changes in soils properties that may result from laundry water application could adversely affect these fundamental functions of the soils. Therefore, the effects of laundry water reuse on soils need a

thorough examination. According to Beltran (1999), knowledge of the chemical composition of reclaimed water is necessary but may not be sufficient to evaluate its suitability for reuse. Other factors such as climate, soil characteristics, drainage conditions and the irrigation method should be considered in order to define the appropriate land use and water management. The water retention capacity and the hydraulic conductivity are the important soil properties that need closer examination for long term use of laundry water. These hydraulic properties of soil depend on soil texture and structure. Furthermore, good drainage conditions are essential to maintain a favourable salt balance in the root zone.

Hence, this research project was dedicated to evaluate the retention and hydraulic properties of the red soils in Toowoomba (a dominant soil type covering more than 95% of the total city area) for reclaimed water reuse, with the project scope limited to the application of laundry water.

1.4 Study Objectives

This research project aims to experimentally determine the retention capacity and hydraulic conductivity of typical soils from Toowoomba. Furthermore, the potential capacity of these soils to store laundry water is examined, accompanying with the analysis of changes in pH and Electrical Conductivity (EC) of the soil, irrigation and drainage water. The main objectives of this research include:

1. Collection of background information on storage and hydraulic properties of soils in relation to water, salt and nutrient loading;

2. Development of experimental protocols to measure soil water characteristic, hydraulic conductivity, pH and Electrical Conductivity (EC) of soils and water using the clay soil from the Agricultural Field Station of USQ;

3. Comparison of soil water characteristic and hydraulic conductivity for disturbed and undisturbed soil conditions to portray garden beds of residential houses in Toowoomba;

4. Analysis of the changes in pH and EC of soil and leachate using typical laundry water for infiltration to determine the quality of drainage water.

Additional but limited information on sodium adsorption ratio (SAR) of soil and leachate was also collected to aid data interpretation and develop recommendations for laundry water reuse.

The detailed project specification is given in Appendix A.

1.5 Dissertation Overview

This dissertation is structured as below to present the project activities and report experimental outcomes in a systematic and concise manner.

Chapter 1: Introduction
This chapter is intended to introduce the topic with a brief outline of the importance and background information on potential reuse capability and options for domestic laundry water. It also includes the statement of the objectives of this project.

Chapter 2: Soil Water Interaction
Chapter 2 provides background information on the properties of laundry water and their potential effects on soils. This chapter also introduces varying properties of irrigation water and their effects on soil hydraulic properties. Previous studies on irrigation and greywater are also reviewed in this chapter.

Chapter 3: Principles of Measuring Soil and Water Properties
Chapter 3 briefly outlines the principles of soil and water sampling and analysis. It provides a basic understanding to the concepts and principles applied to measurements of pH, EC, water retention, water characteristic and hydraulic conductivity of the soil. Furthermore, the chapter explores some of the common methodologies used for the measurement.

Chapter 4: Materials and methods

This chapter outlines the experimental materials and various testing procedures used for the project.

Chapter 5: Results and Discussion

This chapter includes all experimental results and analysis and interpretation of these results examining the effects of laundry water reuse on soil hydraulic properties. This chapter features soil water retention, water characteristic and possible changes in the chemical properties of the studied soil with laundry water application.

Chapter 6: Conclusions and Recommendation

This last chapter of the dissertation summarises main project findings to develop major conclusions arising from the project. Furthermore, this chapter provides possible recommendations for laundry water reuse in residential areas of Toowoomba with indication of further research and development required in this field of investigation.

Chapter 2

Soil and Water Interaction

2.1 Laundry Water Characteristics

2.1.1 Quantity of Laundry Water

Laundry greywater contributes about 34% to the total greywater volume (23% of household wastewater). Toowoomba water used by sectors is characterised by high proportion of water being supplied to dwelling demand. This sector accounts for 63.1% of water use. Figure 2.1 shows the proportion of household water usage in Toowoomba city. About 20% of water demand is used for laundry trough and washing machine. This amount of laundry water generated within household has a high potential for reuse under regulations. The typical Australian household may generate 110 litres of laundry water per day (Patterson 2004).

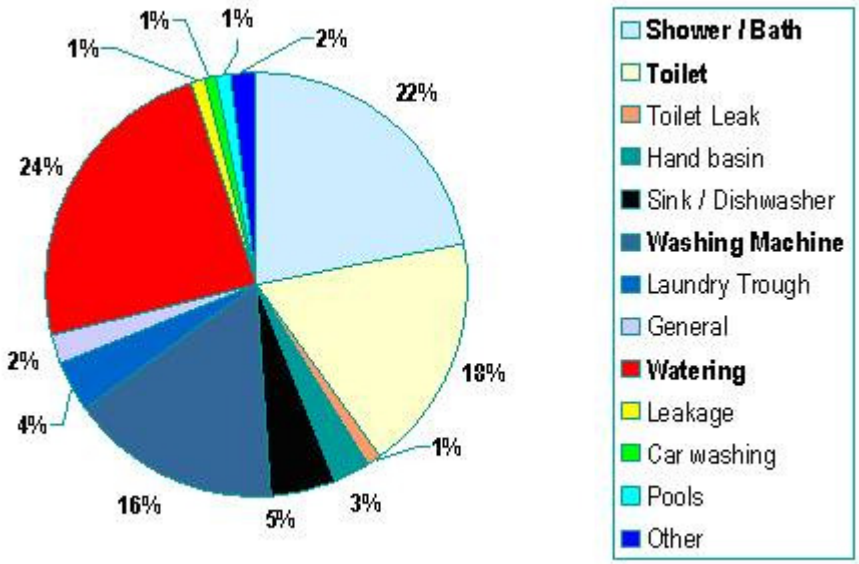


Figure 2.1: Water usage within the household (Toowoomba City Council)

2.1.2 Quality of Laundry Water

Physical:

Total dissolved solids (TDS) represents all inorganic salts dissolved in the liquid or the soil solution in milligram per litre. Typical laundry water has an average total dissolved solids value of 664 ± 50 mg/l (Patterson 1999). The value of TDS of a liquid is related to its electrical conductivity as follows:

TDS (mg/l) = 640× EC (dS/m)

Sub-surface drip irrigation is considered the safest option for applying laundry water on lawns and gardens. However, the presence of TDS in laundry water could limit the performance of the drip irrigation system by clogging of emitters. TDS presented in laundry water has the potential to cause clogging of fine pores when laundry water is applied to the soil.

Biological:

Laundry greywater arising from domestic washing machines varies in quality from wash cycle to rinse cycle (WADH 2002). Greywater effluent can pose considerable health risk due to faecal contamination and viruses. It also contains lint, oils, greases, chemicals, soaps, nutrients and other components (WADH 2002). Brandes (1978) reported greywater to contain considerable amounts of both total coliforms and faecal coliforms of which *E. coli*. being one of the most dominant pathogen. According to Jepperson and Solley (1994), typical laundry wash water contains faecal coliforms of 126 colony forming units (cfu) per 100 ml, while the rinse water contains 25 cfu. They reported combined greywater (bath, laundry, kitchen) containing 1.8×10^5 to 8×10^6 cfu/100 ml. This was substantially higher than that of the laundry water. Faecal coliform counts is an indicator of risk causing human illness through infections, contact with this water is usually avoided.

Biological contamination in laundry greywater is not usually high, except when nappies are washed. Furthermore, rinse water contains a much lower level of pollutant load and cfu that pose much lower threat to public health and the

environment. Therefore, grey water from laundry, particularly rinse water is suitable for reuse (WADH 2002).

Chemical:

Sodium concentration in laundry water is an important chemical property of laundry water for irrigation. Thus, it is the main discussion in this section. Domestic laundry water effluent may contain high amount of sodium increasing sodium adsorption ratio (SAR). Patterson (1999) indicated that large proportion of sodium salts (up to 40% sodium sulphate) in laundry detergents contributes little to the cleaning process, but rather used as 'filler' material for bulking. Furthermore, only a few laundry products (detergents, fabric softeners) manufacturers inform the consumers about the chemical composition of their products. Patterson (1999) showed that laundry detergents with low Na (20 g/wash) produced effluent of preferable quality. From this study with 20 liquid and 40 powder laundry products, only 37 products contributed less than 20 g of Na per wash. Interestingly, all the liquid products tested were within the range of acceptable values. Therefore, if the laundry water was generated using liquid detergents, any adverse effects of Na on soil conditions such as aggregate stability and hydraulic properties would be minimum.

Consumer choice on laundry product could significantly contribute to the proportion of sodium added to the soil environment. If a brand of laundry powder with high sodium (55g per wash) is used by a household, in one year, the application of household's laundry water by irrigating over 500 m^2 of lawn will contribute an equivalent of 1.1 tonnes of sodium chloride per hectare to the soil. The amount is equivalent to adding $\frac{23}{(23+35.5)} \times 1.1 \times 1000 = 432.5$ kg of Na per hectare. On the other hand, about 193 kg of sodium chloride (75.9 kg of Na) per hectare is added to the soil if a low sodium detergent is used. Therefore, the use of a low sodium detergent results in a 84 % reduction in sodium addition with possibly no loss in washing efficiency. It is also possible to further reduce sodium load in laundry water effluent by choosing one of the liquid detergents (Patterson 1996).

2.2 Interaction of Water with Soil

2.2.1 Storage and Retention of Water and Laundry Water

A difference in water potential in soil causes water to flow. The potential difference over distance is referred to as potential gradient. The direction of water flow is in the direction of decreasing potential difference and magnitude proportional to gradient. According to Singer and Munns (2002), liquid water in soil pores and in water films appear as coating the particle surface. Furthermore, the actual movement of water is the process of sliding and slipping of water molecules over other molecules. The flow rates of water in soil depend on a number of factors such as differences in height (gravitational potential gradient), pressure, temperature, dissolved solute concentration (osmotic gradient), soil moisture content (matric potential gradient); and pore sizes and distribution matrix (Hillel 2004).

McLaren and Cameron (1996b) suggested that water movement occurs in soil as tendency of water to attain equilibrium, which makes water to move in soil from regions of high total water potential to those of low total water potential. Therefore, the rate of movement of water over a unit area and time (flux) is a function of the geometric properties of the soil pore space and the potential energy gradient. The movement of water within soils occurs as 'saturated', 'unsaturated' and 'vapour' flow. However, the vapour flow is generally considered to be negligible.

2.2.2. Flow of Water and Laundry Water in Soil

Unsaturated Flow:

Unsaturated flow in soils is more common than the saturated flow. The rate of unsaturated flow is much larger than saturated flow. Unsaturated movement of water occurs within soils that are not completely saturated and where some of the large soil pores are empty. Thus, they do not contribute to the bulk water movement. This movement occurs in a more complicated environment where macropores are filled with air. Thus, flow resistance is greater compared to that of the saturated flow as

only smaller pores are contributing to the flow. In other words, with progressive drying, the remaining water is more tightly held and subjected to more friction and interruptions (decreased pore connectivity) of flow (Singer and Munns 2002). Flow rate is largely due to matric and gravitational gradients. Furthermore, water content and water potential in unsaturated soils can be highly variable spatially and temporally. These factors influence the rate and direction of the flow making it more difficult to measure.

Saturated Flow:

Saturated flow in soil is the movement of soil water where all the pores in the soil are filled with water. Saturated flow in soil is a function of the potential energy gradient that is largely comprised of pressure and gravitational potential. However, in many cases, the presence of entrapped air in the very small pores can prevent soil to reach full saturation and reduce water flow, particularly in swelling clay soils. Examples of saturated zones in soil are the capillary fringe over water table, lower horizons of poorly drained soils, portions of well-drained soils above stratified layers of clay (perched water table), and pores in the upper soil zones during and immediately following a heavy rain or irrigation (Brady and Weil 1999).

2.3 Properties of Clay Soils

2.3.1 Nature of clay soils

Clays are originated from the weathering of the primary minerals contained within rocks. The most common groups of clay minerals (silicate clays) are the kaolinites, montmorillonites and illites. Firstly, kaolinite is the non-swelling clay mineral that is typically developed when the parent rock is subjected to intensive leaching. The weathering process may occur in well drained humid tropical locations where the mineral is produced by the destruction of alkali-feldspars under acidic conditions. Secondly, montmorillonite is the swelling clay mineral that is formed by the alteration of basic rocks or other silicates with low potassium, under alkaline conditions. This clay mineral is responsible for the shrinking and swelling in heavy clay soils. Lastly, illite is developed by the alteration of micas, alkali-feldspars under

alkaline conditions. Kaolinite clay has a far less shrinking and swelling capacity than the other two types (FAO 1995).

Clay particles are characterised by their small size and large surface area. This large surface area has significant effects on the soil properties regarding the retention of water, nutrients, gas and cohesion between particles (Brady and Weil 1999). Furthermore, clay soils tend to be plastic and sticky when wet. These soils are able to retain large quantities of water in their fine porous matrix. This water retention capacity makes these soils attractive for irrigated agriculture. However, these soils usually have a low to very low saturated hydraulic conductivity because of their fine porous matrix that is very poorly permeable.

2.3.2. Infiltration and Permeability of Clay Soils

Factors affecting the infiltration rates include pore sizes, pore size distribution, continuity of the pores and soil structure. It has been observed that most of the infiltration takes place at the beginning when the water is applied to the clay soil. The infiltration then decreases with time and depth. Therefore, most of the water infiltrated is associated with bypass flow, which is the vertical movement of free water along macropores through unsaturated soil horizons. The infiltration would significantly decrease as the macropores become saturated (FAO 1995).

Rainfall intensities and surface mulching conditions are important factors contributing to the infiltration of rain into wet soils. Rainfall with high intensity could cause crusting and sealing of the soil surface. On the other hand, surface mulching and organic matter content would help to absorb the raindrop impact. The infiltration of water into soil is strongly affected by clay content, the structure and stability of the surface soil. Clay soils with high sodium contents are susceptible to swelling and dispersion that would further reduce the soil permeability. As a result, the saturated hydraulic conductivity could become very low (Hubble 1984).

2.3.3 Soil Moisture Storage and Soil Water Content

Soils moisture storage and soil water content are determined by the pore size and continuity pattern. However, these characteristics could be difficult to identify for clay soils due to their shrinking and swelling properties. The shrink-swell processes induce changes in the size and the continuity pattern of soil pores.

Soil water contents at air dryness subjected to 15 bars or 1500 kPa matric suction represent water contents at wilting point. Field capacity is approximated by the soil water contents at air dryness subjected to 0.1 bar or 10 kPa matric suction. However, clay soils are dominated by micropores and their field capacity are usually taken at 33 kPa matric suction. Soil water contents at air dryness and wilting point are increased with the amount and surface area of the clay fraction. Field capacity is influenced by soil structure. Therefore, the available water capacity which is the difference between water contents at field capacity and at wilting point could vary significantly from soil to soil. Clay soils have high clay contents resulting in high amounts of water being retained at wilting point. Thus, the plant available water capacity of clay soils is small even though the soils can hold high moisture at field capacity (Hubble 1984).

2.3.4 Cation Exchange Capacity

Cation exchange capacity (CEC) is a measure of the quantity of readily exchangeable cations neutralising negative charges on soil colloids. CEC is usually expressed in milliequivalents per 100g of soil. CEC depends largely on clay mineral type and is directly related to the surface area. Table 2.1 shows the CEC of the principal clay minerals. Montmorillonite clay has the highest CEC compared to the other two clay minerals.

Table 2.1: CEC and specific surface area of the principal clay minerals (Brady and Weil 1999)

Clay mineral	Surface area (mg^2/g)	Internal surface area	External surface	CEC (meq/100g)
1:1-type lattice clays, Kaolinite	5 -20	none	low	3 -15
1:2-type lattice clays, Illite Montmorillonite	100 -200 700-800	Medium Very high	Medium High	10-40 80-150

Exchangeable Cations are cations absorbed on the soil surface. These cations can be exchanged for other cations presented in the soil solutions. The exchangeable bases include calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+). In most agricultural soils, these exchangeable bases occur in the order listed with the large quantities being occupied by Ca^{2+}. On the other hand, sodium is very low in most soils (Grant 1982).

The main salts found in soils solution are:

- Cations: calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+)
- Anions: chloride (Cl^-), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-) and nitrate (NO_3^{2-}).

2.4 Effects of Ion Concentration of Irrigation Water on Soil Properties

2.4.1 The Diffused Double Layer (DDL)

The effect of sodium in greywater on the dispersive properties of soil is well documented (Patterson 1996), and it can be examined through the concept of the Diffused Double Layer. (DDL is sometimes referred to as the 'Electric Double Layer' or 'Electrostatic Double Layer').

In terms of the quality of water applied, increase in sodium percentage and electrolyte concentration could have significant effects on the infiltration capacity of a clay soil through the function of the DDL and the hydraulic conductivity (K).The diffuse double layer is a model that describes the relative ion distribution in the proximity of a charged surface such as clay colloids. The distribution of cations and anions surrounding negatively charged soil colloids vary with distance from charged surface. For example, the cation concentration gradually decreases from a high concentration near the colloid surface to a lower state in the bulk solution. On the other hand, the deficiency of anions occurs near the colloid surface, and hence, the concentration of anions gradually increases with distance until it reaches the equilibrium state in the bulk solution as shown in Figure 2.2. These distributions are the result of the attraction of the negative charges to the colloid surfaces (clay and organic matter).

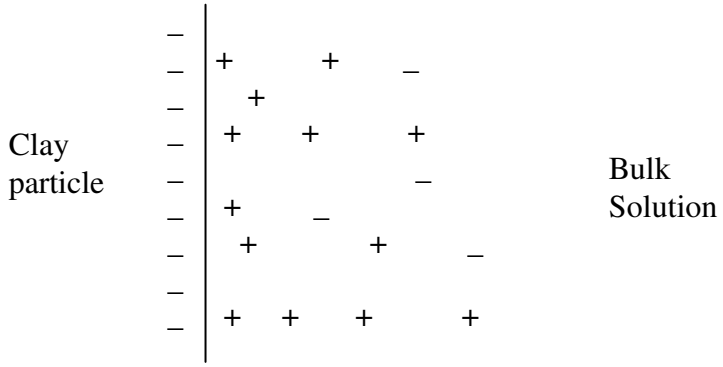


Figure 2.2: Distribution of cations (positive) and anions (negative) in the DDL (adapted from Marshall and Holmes1988).

2.4.2 The Effect of Ion Valency and Concentration on the DDL

DDL plays a significant role in affecting soil physical and chemical properties. Firstly, soil water would try to flow towards the colloid surface in attempt to dilute the high concentration. As a result, an osmotic pressure arises between the clay colloid sheets. This pressure creates expansion and swelling of the clay colloidal material. Secondly, the width of the DDL contributes directly to the physical

properties of the soil. The stability of the soil aggregates and structure increases as the width decreases, and vice versa. On the other hand, the width of DDL is also a function of the cations' valency and the concentration of the bulk solution (Figure 2.3). The width of DDL could be minimised by introducing higher valency ions (e.g. Ca^{2+} with gypsum application) and increasing its bulk solution concentration.

The distance that the DDL extends from the colloid surface (d_{DDL}) is determined by:

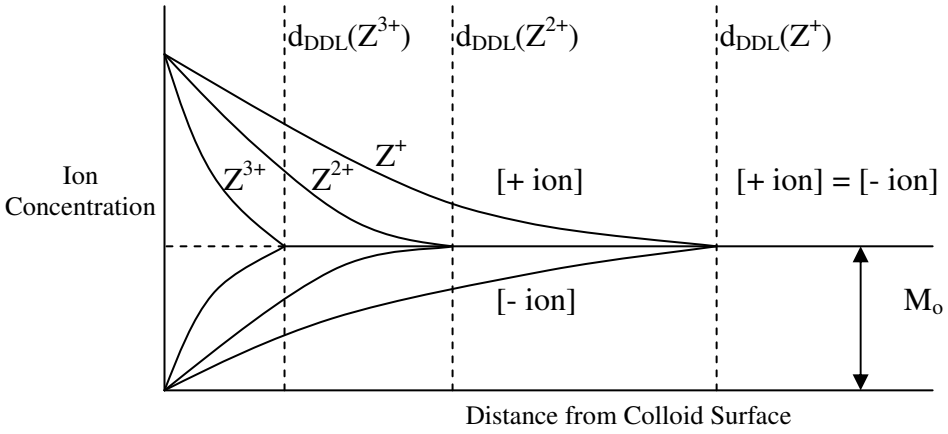
$$d_{DDL} = \frac{1}{KZ\sqrt{M_o}}$$

Where:

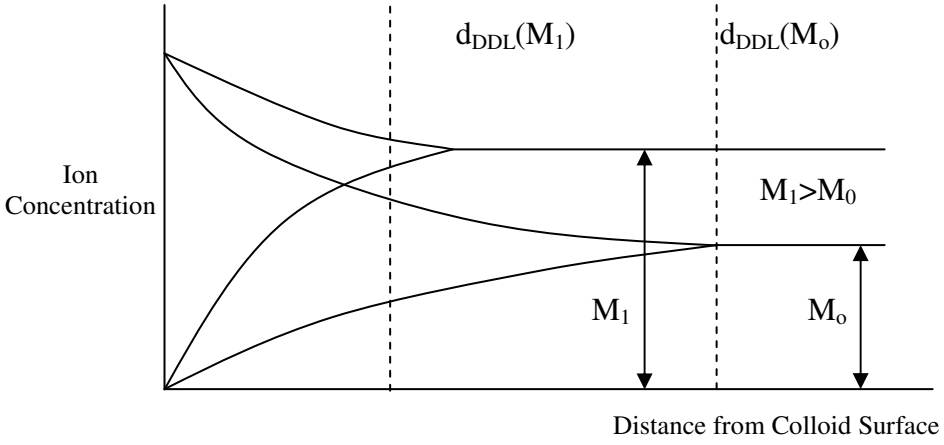
K is a constant dependent of the system temperature

Z is the valency of the dominant ion

M_o is the concentration of the ions in the bulk solution in charge unit ($cmol_c/kg$)



(a) The effect of Ion valency on the DDL



(b) The effect of bulk solution concentration on DDL

Figure 2.3: Effects of cation valency and concentration on DDL (adapted from Hillel 2004)

In (a), the width of DDL is shown as vertical dashed lines for various ions of varying valency. In (b), the effect of increasing the concentration of an introduced ion (M_1) on the width of DDL is shown. Aggregate stability and the presence of swelling clays can have a significant impact on infiltration via DDL. Increase in sodium concentration in infiltrating water could negatively affect the stability of the soil as it increases the width of DDL causing dispersive of colloids. Sodium ion has low cation valency (one positive charge) that could increase the width of DDL. The greater the width of DDL means less stability of the soil aggregates. On the other

hand, an increase in electrolyte concentration (Ca^{2+} from gypsum) could narrow the width of the DDL increasing the structural stability of soil and facilitating infiltration.

2.4.3 Effects of Ions on Soil Hydraulic Conductivity (K)

With respect to the effect of ions on soil hydraulic properties, a relationship similar to DDL is expected when the concentration of Na^+ is increased in the soil solution together with the electrolyte concentration in soil. Infiltration of water is dependent on the hydraulic conductivity (K). A stable value of K is preferable in maximising infiltration capacity, while decreasing K lowers infiltration capacity. The effects of irrigation water quality (in terms of electrolyte concentration and the exchangeable sodium percentage) on the hydraulic conductivity of the soils are shown graphically in Figure 2.4.

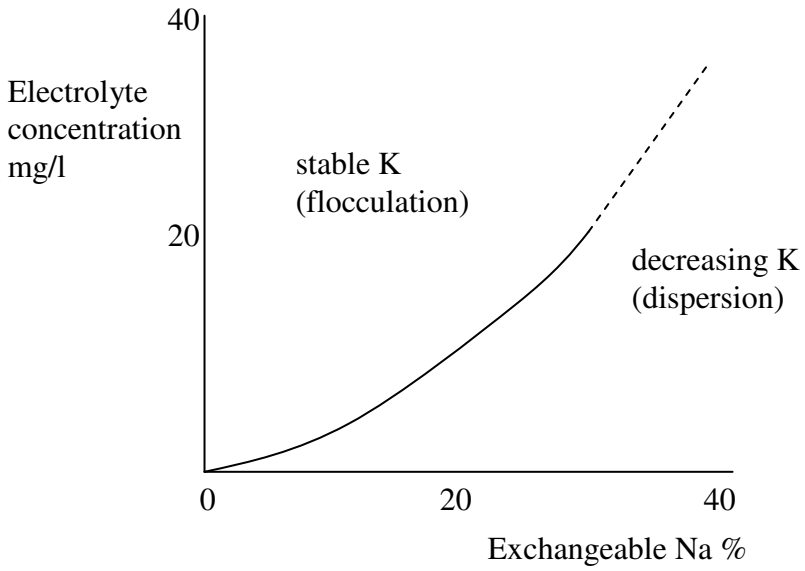


Figure 2.4: The effect of exchangeable sodium percentage and electrolyte concentration on hydraulic conductivity (K) of soil (adapted from Turner et al, 1984)

If the water has high electrolyte concentration and low exchangeable Na %, stable values of K can be achieved and resulting in the flocculation of the colloids (stable aggregates). A stable value of K for soils is preferable as it enhances the flow of water. However, soil dispersion would occur if the infiltration water has a high concentration of Na and low electrolyte concentration resulting in unstable K, decreased infiltration capacity and wetting depth. Even slightly saline water with low electrolyte (salt) concentration will not disperse soil if the salts do not contain sodium. Therefore, some saline water containing high concentration of Na will disperse soil and reduce hydraulic conductivity due to dispersion and consequent blockage of pores.

2.5 Effects of Irrigation Water Quality on Soils

2.5.1 Effects of Saline Water

The quality of irrigation water is an important factor for the management of soil. Irrigation water with high amount of dissolved salts such as saline water has the potential to adversely effect the environment. Secondary soil salinization and poor drainage quality are the typical impacts of saline water irrigation.

Table 2.2 shows a classification of waters from different sources which allows a comparison among the salinity of drainage water, groundwater and surface water. This classification was based on the electrical conductivity (EC) and total dissolved solids (TDS) of the water. On the other hand, Table 2.3 provides guidelines for interpretation of water quality and the corresponding potential problems in terms of salinity and infiltration.

Table 2.2: Classification of water (Rhoades et al. 1992)

Type of water	EC (dS/m)	TDS (g/l)	Water Class
Drinking water	< 0.7	< 0.5	Non-saline
Tap water	0.03	0.02	Non-saline
Irrigation water	0.7 – 2.0	0.5 – 1.5	Slightly saline
Laundry Water	0.39	0.25	Slightly saline
Primary drainage water and groundwater	2.0 – 10.0	1.5 – 7.0	Moderately saline
Secondary drainage water and groundwater	10.0 -20.5	7.0 -15.00	High saline
Very saline water	20.0 – 45.0	15.0 – 35	Very highly saline
Seawater	> 45.0	> 35	Brine

Table 2.3: Guidelines for interpretations of water quality for irrigation (Ayers and Westcot, 1985)

Potential irrigation problem	Units	Degree of restriction on use		
		None	Slight o moderate	Severe
Salinity (affects crop water availability)				
EC	dS/m	< 0.7	0.7-3.0	>3.0
TDS	mg/l	< 450	450-2000	>2000
Infiltration (affects infiltration rate of water into the soil)				
SAR = 0-3 and EC =		> 0.7	0.7-0.2	<0.2
SAR = 3-6 and EC =		> 1.2	1.2-0.3	<0.3
SAR = 6-12 and EC =		> 1.9	1.9-0.5	<0.5
SAR = 12-20 and EC =		> 2.9	2.9-1.3	<1.3
SAR = 20-40 and EC =		> 5.0	5.0-2.9	<2.9

Salinity in the form of sodium can directly affect soil properties through the phenomena of swelling and dispersion. Sodium is a positively charged cation that interacts with the negatively charged layers of clay particles. The clay negatively charged layers are known as platelets. The electrophoretic mobility of the clay platelets increases as the concentration of sodium increases. This process results in swelling and dispersion of clay particles thus impacting on soil permeability (Halliwell et al. 2001). With respect to the concept of the diffuse double layer, the increased concentration of sodium would result in widen width of the DDL (as discussed in sections 2.4).

2.5.2 Water With High SAR

The effects of water quality on soil properties are normally examined using the concepts of Sodium Adsorption Ratio (SAR), and Electrical Conductivity (EC). SAR is useful because it considers the relative distribution of monovalent and divalent cations in irrigation water. SAR is the relationship of soluble sodium in water or as the exchangeable ions in the solution, expressed by the following equation:

$$SAR = \frac{[Na^{+}]}{\sqrt{0.5 \times [Ca^{2+} + Mg^{2+}]}}$$

where the concentration of ions, denoted by square brackets, are in milliequivalent per litre (meq/L) in water or soil.

EC is an indicator of the total ion concentration in the water or in the soil solution, (dS m^{-1}) at 25 ºC. It is the reciprocal of electrical resistivity and a measure of soluble salt content in solution.

Previous studies on greywater reuse have shown SAR to be a good indicator water quality altering physical and plant biological processes (Patterson 1991). His study showed that SAR values as low as 5 reduced saturated hydraulic conductivity (K_{sat}) by over 2 orders of magnitude. In addition, ANZECC (1992) reported that SAR value of 5.5 can negatively affect plant growth and soil structure if the soil has an exchangeable sodium percentage (ESP) of 10-15%.

Patterson (1996) examined the impacts of irrigation water quality on (K_{sat}) of soils by varying SAR (1, 3, 8 and 15) and EC values; and infiltrating the effluent through undisturbed samples of soils in replicated trials. Six soils types including a red-brown earth were examined in his study. For A horizon, the overall K_{sat} decreased by 50% from SAR0 to SAR3 and by 79% from SAR0 to SAR15. On the other hand, the overall loss in K_{sat} of the subsoil was in the order of 30% from SAR0 to SAR3, but 60% from SAR0 to SAR 15. These results demonstrated that increasing SAR in

irrigation water decreases K_{sat} of the exposed soil, especially that of the surface soil. Thus, long term potential of soil to maintain its natural hydraulic conductivity could be reduced when SAR of irrigation water is high. In addition, the reduction in K_{sat} would reduce the expected lifetime of the areas used for disposal of wastewater due to discharge at surface with the scope of contaminating surface water.

Where drainfields fail due to a reduction in K_{sat}, the effluent enters the surface drainage system via run-off and is expected to carry nutrients (phosphates and nitrogen) and other organisms such as faecal coliform that would likely contaminate waterways (Patterson,1996). Therefore, to maintain desirable soil conditions, soluble calcium and magnesium salts (gypsum) need to be applied to reduce SAR while increasing EC to reduce adverse environmental impacts of wastewater irrigation.

Speirs and Cattle (2004) studied the effects of irrigation water of varying SAR in several Vertosols. They pointed out that the structure of Vertosol surface horizons were significantly affected by the sodium concentration of the irrigating solution. Irrigation water of high SAR decreased the connectivity of macrospores. Reduced connectivity of macropores could result in lower infiltration rate and reduced hydraulic conductivity of the soils.

Emdad et al. (2004) studied the effects of water quality on soil structure and infiltration under furrow irrigation. Water with three different levels of sodium concentration (SAR = 0.9, 10 and 30) was applied as an alternative treatments to a clay loam soil. They found an increase in bulk density and decline in infiltration with irrigation water of moderate and high EC-SAR due to reduced size and connectivity of micropores. In this study, application of water with high SAR reduced aggregate stability, increased the bulk density of both the surface and underlying soil, and reduced the total depth of infiltration and final (steady-state) values of infiltration rate. The total depth of infiltration was reduced by 15% for the high EC-SAR treatment. This infiltration reduction was associated with the formation of the 5 cm thick disturbed surface layer. Furthermore, the decrease in final infiltration rate with successive applications of moderate and high EC-SAR water implied that the change in soil physical behaviour was influenced by the chemical properties of soil solution.

2.5.3 Water With High ESP

The effects of exchangeable sodium percentage on hydraulic conductivity and swelling of clay soils were examined by McIntyre (1979). In this study, the soil hydraulic conductivity and swelling were examined in relation to the exchangeable sodium percentage (ESP), clay content and type, and the degree of subplasticity. The property of subplasticity referred to the stability of soil materials in their reaction with water. Thus, soils with high subplasticity behave more like sands or gravels than heavy clays. The study indicated that there was a continuos and initially very rapid decrease in soil hydraulic conductivity when water with increasing ESP was applied. Furthermore, ESP had significant effects on the hydraulic conductivity of the normal plastic soils regardless their clay contents and types. On the other hand, ESP did not have any effect on the hydraulic conductivity of the subplastic soils, and swelling was small compared to their clay contents. The author argued that an ESP value much less than 15 should be accepted as the value at which the soil physical properties can be adversely affected. The article suggested an ESP value of 5 for Australian soils.

Alperovitch et al. (1985) suggested that the reduction of hydraulic conductivity in soils with high exchangeable sodium and electrolyte concentration was primarily associated with an increase in tactoid swelling. This swelling resulted in reduced diameter of soil pores, and therefore, increased the resistance to flow.

Ten years later, Crescimanno et al. (1995) conducted an experiment to investigate the effects of ESP on soil structure and hydraulic characteristics. The study was carried out to analyse the response of two soils to ESP values of up to 15. Both saturated and unsaturated hydraulic conductivities were examined using the constant-head method and one-step outflow experiments respectively. The results showed that ESP from 2 to 5 caused the reduction in aggregate stability, and 25% decrease in hydraulic conductivity. Therefore, they suggested the ESP values of 2 to 5 as indicating values of which the greater ESP values would create adverse effects on soil properties .

2.5.4 Consequences of Wastewater Irrigation

The concept of recycled water and reuse has been recognised as an alternative to urban water management. There have been a number of studies and researches to investigate the effects of irrigation water quality on the environment. Between the years from 1955 until the present, many researches have been carried out at different methodologies and scales to analyse the possible impacts of the reuse on the properties of soils that receive the water. However, even some studies were conducted as early as 1955, there were not many published literatures regarding the effects of greywater reuse on soils until the 1990s. The investigation has been intensified over the past five years due to the droughts and possible shortage in water supply. There are a number of laboratory and field studies which have reported the effects of altering the water quality on various soil properties.

AWRC (1992) expressed some concerns that irrigation with reclaimed wastewater without proper control of salinity has the potential to create serious environmental problems. This concern was supported by a banana irrigation trial of Battye-Smith (1992). The banana irrigation trial used effluent with the SAR value of 4.6 that resulted in accelerated leaching of salts and an increased salinity of the ground water.

Coppola et al. (2004) conducted a multidisciplinary research to verify the consequences of urban wastewater irrigation on both the hydraulic and dispersive properties of soils in South Sardinia, Italy. In this research, ten undisturbed soil monoliths with 120 cm in height and 40 cm in diameter were collected. Time domain reflectrometry (TDR) probes were inserted horizontally at 15 cm intervals (starting from a depth of 5 cm from the soil surface) to measure initial water content distribution in the soil columns. They measured soil hydraulic and solute transport properties before and after the application of wastewater. With wastewater application, the sol surface developed a disturbed layer with reduced porosity and dominated by narrow pores that decreased both water retention and hydraulic conductivity. This process could be induced by the compaction, dispersion and aggregate destruction of the disturbed layer (surface sealing). This research

concluded that the changes occurring in the disturbed soil layer affected the mean hydrological behaviour of the whole soil profile.

Amoozegar et al. (2004) studied the effect of grey water on hydraulic properties of soils in North Carolina. The main objective of this study was to assess the impact water generated from laundry and dishwashing machines of single-family home on soil hydraulic properties. K_{sat} of each of the studied soils were measured using tap water, water generated from laundry, and water generated from dishwashing machine. They reported that the application of grey water from laundry and washing machine resulted in substantial reduction in K_{sat} within a few days. Furthermore, Toze (2005) suggested that the reduction of hydraulic conductivity is one of the major impacts of laundry water reused on soils. Other laundry water characteristics that have been identified to reduce hydraulic conductivity include nutrients which cause excess growth of microorganisms in the soil, the present of suspended solids, and the interaction of dissolved organic matter within the soil profile (Magesan et al. 2000).

From the literature reviewed above, there is considerable evidence that both physical and chemical properties of soils are affected when soils are irrigated with wastewater.

Chapter 3

Principles of Measuring Soil and Water Properties

3.1 Principles of Soil Sampling

It is necessary to produce test samples that would represent the soil under investigation. According to Reed and Rigney (1947), sampling errors are commonly much grater than analytical errors. Therefore, it is necessary to minimise the sampling errors. Rayment and Higginson (1992) suggested that sampling errors could be minimised by using sampling equipment and containers known to be free from relevant contamination.

Misra (1996), pointed out that if materials such as rocks or tree roots which have significantly different compression characteristics form soil are presented, ambiguous results may be obtained with physical measurements of soil in the field. Furthermore, results of soil chemical analysis would not yield a value that describes the property of the soil as a whole, if the sample analysed is not representative (Tan 1996). This view is supported by Clinne (1945) that the analytical value can serve as an accurate description of the soil property only if the gross sample accurately represents the whole soil from which it was taken. Therefore, producing the representative samples is critical to the validity of the analytical results. However, the size and accuracy of sampling are determined by many factors including the cost of sampling.

3.1.1 Size and Accuracy of Sampling

The size of sampling is referred to (1) size which is the quantity of samples and (2) the number of sample to be taken. There are a number of factors influencing the size of sampling such as the coarseness of the material, objective of the analysis and the desired accuracy. However, little information on this subject is available in soil

literature (Tan 1996). Furthermore, the size of the sampling is significantly determined by the cost. Although frequently the number of samples is decided arbitrarily, both quantity and the number of samples taken are often restricted by the economic considerations.

Rayment (1985) provided a method of calculating the preferred number of sub-samples using a statistical analysis. In practice, a suitable number of samples would usually involve making a composite from around 15 to 30 sub-samples (Rayment and Higginson 1992).

3.1.2 Mechanics of Sampling

Soil sampling tubes, augers spades and/or shovels are tools that can be used to collect soil. Shallow sampling includes collection of undisturbed and disturbed cores near surface of soil. For some measurements, the best result will be obtained by maintaining the natural structure of the soil (undisturbed). However, loose material that has been broken or sieved would be more appropriate for others measurements such as pH and EC (Tan 1996). Table 3.1 shows the preferred specimen types for soil physical determinations.

Table 3.1: Preferred sampling of soil (adapted from Tan 1996)

Measurement	**Preferred**	**Alternative**	**No. of Replicates**
Matric potential: -10 m to -150 m	Small aggregates (1-5 mm)	Ground and sieved soil (< 2 mm)	1-2
K_{sat}, laboratory	Undisturbed large core	Undisturbed small core	3-5
Particle size distribution	Ground and sieved soil (<2mm)	-	1
Bulk density and pore space relations	Undisturbed small core	Large clod	3-5

Undisturbed samples of soil are collected within a box (die) or a tube which is driven carefully into the soil. The sample is cut loose with a knife. Undisturbed samples are needed for bulk density measurement and soil fabric or thin section analysis.

Disturbed samples are collected with an auger, a tube or a core sampler. The centre portion of the sample is cut, lifted and placed in a clean plastic bag. The collected units may be mixed in a plastic bucket thoroughly until a completely homogeneous mixture is attained (Tan 1996), ground and remoulded to produce disturbed cores.

3.1.3 Preparation of soil cores

Care must be taken to avoid contamination and to prevent the occurrence of further chemical reactions. According to Tan (1996), air drying is the most accepted procedure of sample preservation and samples should not be allowed to stay moist for extended period of time. Furthermore, drying at elevated temperature must be avoided to prevent physical and chemical changes. A drying temperature of not exceeding 35°C is recommended.

Tan (1996) recommended air drying of soil by spreading it in drying trays in an oven at 40 °C, the soil then can be broken down by grinding. The grinding can be done by using a mortar and pestle, rolling pin or mechanical grinder. However, the soil should not be subjected to a force that is capable of breaking the individual sand, silt or clay particles.

A similar practice was conducted by Misra (1996). In his experiment, the soil was air dried, passed through a 2 mm sieve and stored until further use. In the preparation of soil cores, the soil was remoulded, and then a known weight of wet soil was packed in a clear acrylic tube to a desired bulk density. A hydraulic loading frame with a detachable plunger equal to the inner diameter of the tube was used in the packing. He reported that preliminary attempts to produce soil cores with minimum variation in bulk density indicate the need to compress soil from both ends of the cores. Therefore, to produce such cores, the process is as follows:

a. attach two tubes of identical diameter and height to each other by masking tape
b. place nine-tenth of the required quantity of soil in the tube
c. compress the soil to desired depth (using a plunger)

d. remove the upper tube

e. trim the top of the core to obtain a flat surface

f. place the core upside down

g. attach another identical tube to the top of the call

h. add the remaining one-tenth of the soil

i. compress to the desired depth

The bulk density can be derived from the final weight of the soil assuming no water loss during the preparation. In addition, some cores with deviation from the desired density by 0.05 Mg m^{-3} were not used in further measurement.

3.2 The Solid Phase

3.2.1 Bulk Density

Soil bulk density (BD) is the mass per unit volume of soil and it has application to almost all of the soil studies and analyses. BD is required to determine the degree of compactness as a measure of soil structure. BD provides an indicator of the soil aeration status. Furthermore, BD is used to convert soil moisture content from gravimetric (g/100g) to volumetric (cm^3/cm^3) base.

$$Bulk\_dendity = \frac{Weight\_of\_soil(oven-dry)}{Bulk\_volume} \qquad (kg/m^3 \text{ or } g/cm^3) \quad \text{eq.3.1}$$

The bulk volume refers to the volume occupied by the solid particles and the pores in a soil ped or soil clod. Since soil BD is affected by moisture content, the BD can be measured on an oven-dry basis or on a weight of a moist soil. However, BD based on oven-dry weight is commonly used. The spatial variability of bulk density is about 10% of the mean from various literatures (Dane & Topp 2002). According to Tan (1996), the two common methods of BD measurement are that of the disturbed and undisturbed (core or clod) soils. In terms of irrigated soil, the core method is preferred (Loveday 1974).

In core method, a cylinder is inserted into the soil where the sample is obtained within the cylinder. Therefore, the volume of the cylinder is that of the sample. This method is limited by the physical properties of the soil. The soil must remain within the cylinder on withdrawal from the ground. Soils with low coherence such as a sandy soil may not remain in the cylinder. On the other hand, soils must be weak enough to allow the insertion of the cylinder without creating any significant interruption to the sample. Therefore, the collection of soil cores with low coherence may need a special apparatus such as a piston sampler in Sheppard et al. 1993 (Loveday 1974), while clayey soils may need to be moist before the collecting commence.

3.2.2 Pore Spaces

The portion of soil volume occupied by air and water is pore space. Pore space is sometimes called *void* in micromorphology. Total porosity of a soil is determined by its texture and structure. Therefore, sandy soils (coarser texture) have a total porosity ranking from 35% to 50%. On the other hand, silty and clayey soils (finer texture) have a total porosity ranking from 40% to 60%. This is because soils with finer texture have a larger proportion of pore space than that of the coarser soils. Soils or subsoils that are subjected to compaction may have a total porosity as low as 25% to 30% (Tan 1996).

Soil pores may be classified into micropores and macropores. Micropores have the main function to retain or hold soil moisture. On the other hand, macropores are responsible for air and water movement within soil. Air and water move rapidly in sandy soils because of their dominant macropores. This movement is comparatively restricted in clayey soils due to their dominant micropores, but these fine textured soils have a greater water holding capacity. Tan (1994) suggested that the simplest method to determine pore space is through the measurements of particle density and bulk density. The percentage of pore space can be calculated as follow:

$$\%PoreSpace = 100 \times \frac{ParticleDensity - BulkDensity}{ParticleDensity} \qquad \text{eq.3.2}$$

3.3 Soil pH Measurement

3.3.1 Principles and Definition

Soil reaction, the degree of acidity or alkalinity in soils is determined by the hydrogen ion (H^+) concentration in the soil solution. The term pH was introduced by Sorensen in 1909 (Tan 1996)to characterise the facts that an acid soil contains more H^+ than OH^- ions, whereas an alkaline soil has more OH^- than H^+ ions.
pH is defined as the negative logarithm of the free hydrogen ions concentration.
$pH = -\log(H^+)$ or

$pH = \log 1/(H^+)$

The unit of H^+ is measured in activity or moles/L (grams/L since one mole of hydrogen ion equals to one gram). Activity is part of the actual H^+ ion concentration that participates in chemical reactions. The higher the pH value, the lower the H^+ ion concentration and the less acidic the solution is. In aqueous solutions, the pH scale ranges from 0 to 14. In a neutral solution, the concentration of H^+ ions is equal to that of the OH^- ions (pH = 7, H^+ = 0.0000001g/L).

Hydrogen ions may be absorbed on the soil colloidal surface, or as free H^+ ions concentration in the soil bulk solution. The absorbed H^+ ions contribute to the *reserve acidity* or the *potential* or *exchangeable acidity* of the soils. On the other hand, the free H^+ ions contribute to the *active acidity* of the soils. Soil pH takes into account this active acidity.

Soil *buffer capacity* is the resistance to change in soil reactions. In agricultural practice, lime is added to acidic soils to react with the *total acidity* (active plus reserve acidity). However, the total acidity may be more difficult to reduce for soils with greater reserve acidity (*buffer capacity*). Furthermore, the reserve acidity is determined by the cation exchange capacity of the soil. Table 3.2 shows the various types of soil reactions corresponding to pH values.

Table 3.2: pH and Soil Reaction (Tan 1996)

pH	Soil Reaction	pH	Soil Reaction
7.0 – 6.0	Slightly acid	7.0 -8.0	Slightly alkaline
6.0 – 5.0	Moderately acid	8.0 -9.0	Moderately alkaline
5.0 – 4.0	Strongly acid	9.0 -10.0	Strongly alkaline
4.0 – 3.0	Very strongly acid	10.0 -11.0	Very strongly alkaline

3.3.2 Factors Affecting pH Measurement

Suspension Effect

When the water is separated from the soil by centrifugation or gravitational forces, the pH of a soil suspension is usually lower that of the supernatant. This is because the H^+ ion concentration is higher at the cay surface than in the bulk solution. In a soil suspension, the electrode registers the H^+ ions both at the surface of the soil and in the solution. On the other hand, in a soil supernatant, the electrode registers only ion concentration of the bulk solution. The difference in the result is called the suspension effect.

Dilution Effect

Soil pH can be conducted under different soil:water ratios where different results are usually obtained. The common ratios are 1:1, 1:2, 1:5 and 1:10 where higher soil:water ratios would produce higher pH (Jackson 1958). The higher pH value is resulted when the H^+ ion concentration becomes diluted. A soil:water ratio of 1:1 or 1:2 is similar to the soil water under natural conditions, but they could be too sticky for the measurement. According to Loveday (1974), it is desirable to have information on pH and EC of the soil solution at water contents occurring under field conditions. There are a number of methods to obtain these values at field conditions, but these methods could be time consuming and complicated. Therefore, the measurement at higher soil water content (1:5 soil-water suspension) has been accepted and widely used in Australia.

Sodium Effect

The sodium effect occurs in the pH measurement of alkaline solutions. At high pH, hydrolysis of Na ions causes a decrease in pH observed. To reduce the error causing by this sodium effect, the electrode is usually standardized with a buffer solution with the same amount of Na as the test solution.

Water pH Versus Buffer pH

The buffer pH is measured in 0.01 *M* $CaCl_2$ or 0.1 *M* KCl instead of water. This method has a number of advantages. It decreases the effect of the junction potential of the calomel reference electrode, prevents soil dispersion, and equalises the salt content of soil. Usually the pH of this solution is lower than that in water (Tan 1996).

3.3.3 Methods for pH Measurement

There are two main methods for determining soil pH, which are the colorimetric and potentialmetric methods. Firstly, the colorimetric method makes use of suitable dyes or acid-base indicators. The indicators change colour with the hydrogen ion activity (Black et al. 1965). The colorimetric method is primarily confined to field test kits which are capable of giving results that agree within 0.3 pH unit with those obtained from the electrometric method (Mason and Obenshain 1939). Therefore, this method is applied in the field as a rapid test, in which colour is used to indicate pH levels. Secondly, the potentialmetric method uses electrodes to measure the H^+ ion concentration in the soil solution and there are a large variety of electrodes available.

3.3.4 Soil pH Affecting Plant Growth

Nearly all plant nutrients are available in optimal amounts in soils with a slightly acidic reaction. Therefore, most plants grow best in soils with this pH range. However, acidic soils (pH<6.0) are likely to be deficient in some available nutrients, especially Ca, Mg and K. In strongly and very strongly acid soils, some nutrients may exit in very high amounts that are toxic to plants. Al, Fe and Mn become exiting in toxic quantities in strongly acid soils due to their increased solubilities. On the

other hand, some nutrients such as Fe, Mn, Zn and Cu become unavailable in alkaline soils. Furthermore, a number of other soil properties and processes such as clay mineral formation and microbial activity are affected by soil pH. As a result, Jackson (1956) indicated that the most important soil chemical property was soil pH.

3.4 Electrical Conductivity (EC)

3.4.1 Principal and Definition

Gregorich et al (2001) defined electrical conductivity (EC) as the reciprocal of electrical resistivity, the conductivity of electricity through water or an extract of soil; expressed in decisiemens or siemens per meter (dS m^{-1}) at 25ºC. Pure water is a very poor conductor of electric current. On the other hand, water containing dissolved salts conducts current approximately in proportion to the amount of salt present. In other words, EC is a measurement of the soil solution's capacity to conduct an electrical current. Therefore, EC of the solution is associated with the ions (electrolytes) or salt concentration in the solution. EC has a direct relationship with the electrolyte concentration. It increases proportionally to the concentration of the electrolyte in solution. Therefore, EC is a common measure for salt concentration in both water and soil (Black et al. 1965).

3.4.2 Factors Affecting EC Measurement

The total ions concentration and the relative proportions of the dissolved ions have influences on the actual EC. EC is affected by the temperature at which the measurement is undertaken, temporal variations in electrolyte concentration and composition due to rainfall, drainage, weathering and fertilisers. Simply increase soil moisture would result in decreased EC of the soil solution and vice versa. The choice of preparing a soil-water extract and for measuring depends on the purposes and required accuracy. Generally, the higher the water content at which the extract is obtained, the less representative the extract is of the soil solution in natural conditions. However, EC measurement at 1:5 soil:water ratio is commonly used.

EC of soil solution can be conveniently measured by using an *electrode*, and recording the EC of each suspension immediately after the final stirring.

3.5 Water Retention and Moisture Characteristic

3.5.1 Water Retention

Water is held in the soil by both adhesive and cohesive forces. Adhesion is referred to the attraction of the solid soil particles for water, whereas cohesion is the mutual attraction between water molecules. In addition, another force is the capillary force, where water is adsorbed on the micropores or capillaries (Tan 1996).

Water retention is the amount of water retained and stored in a soil after watering and subsequent drainage. The two important concepts in water retention are *field capacity* and *permanent wilting percentage* or *wilting point*. The soil moisture contents at these two points are referred to as the upper and lower limits of the plant available water capacity. Field capacity was defined as the amount of water remaining in a well-drained soil when the velocity of downward flow into unsaturated soil has become small. However, it is now defined as the percentage of water remaining in a soil 2 or 3 days after having been saturated, and after free drainage has practically ceased (Rich 1971). Permanent wilting point is the moisture content of the soil at which the plant at a certain stage of development wilts and does not recover turgor when placed in a certain dark humid chamber overnight. Soil moisture content at 15 bars suction was chosen as a suitable mean figure at which permanent wilting may be said to occur (Loveday 1974).

3.5.2 Soil Moisture Characteristic

Soil moisture characteristic or moisture retention curve relates the amount of water retained in a soil (volumetric water content) to the energy state (potential) of that water. The relationship obtained depends on whether the soil is wetting (sorption) or draining (desorption). The typical sorption and desorption soil moisture characteristic

curves are shown in Figure 3.1.

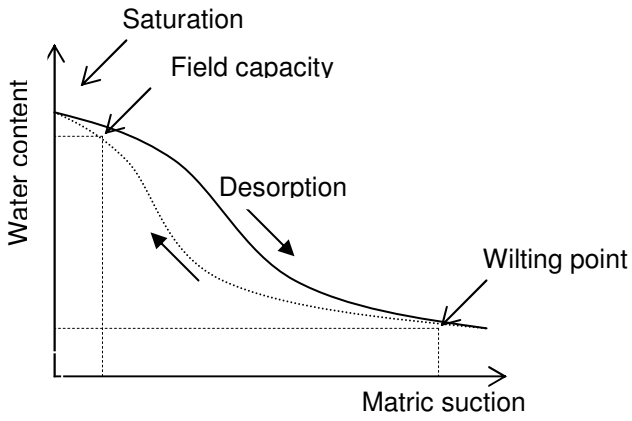


Figure 3.1: Soil water retention curves (Hillel 1971, p. 66)

The typical moisture retention curves give the following information about soil:

- The soil porosity corresponds to the volumetric water content when the soil is saturated near zero matric potential.
- The soil pore size distribution is dedicated by the slope and form of the curve. In clay soils, high water content is held at low water potential (high suction) due to the abundance of adsorptive surface and fine ports.
- The soil field capacity usually corresponds to the water content at -10 to -30 kPa matric potential.
- The wilting point water content usually corresponds to about -1500 kPa matric potential.
- The available water holding capacity, which is the amount of water held between the field capacity and the wilting point.

3.5.3 Factors Affecting Soil Moisture Characteristic

The water retention curves of soils depend mainly on their soil texture and structure. Firstly, soil texture is the range of particle sizes in a soil, which is the proportion of sand, silt and clay. Therefore, soil texture has a primary effect on total porosity and pore size distribution. Sandy soils have a smaller total porosity compared to clayey

soils due to the lack of strong aggregation and higher bulk density. Therefore, the water contents of sandy soils are usually lower than those of clayey soils. Furthermore, sandy soils are dominated by macropores which allow rapid draining at low suctions. The lack of micropores in sandy soils results in the soils having very low moisture contents at high suction. On the other hand, clayey soils generally have high water contents at saturation, drain slowly with increasing suction, and have much higher soil water contents at higher levels of suction. These comparisons are illustrated in Figure 3.2 below:

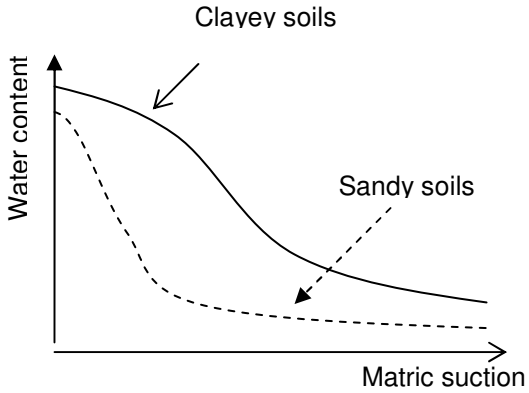


Figure 3.2: The effect of texture on soil water retention (Hillel 1971, p.64)

Secondly, soil structure is the combination or arrangement of primary soil particles into secondary particles such as aggregates, units or peds. As a result, soil structure, especially the degree of aggregation has a significant influence on the total porosity and pore size distribution within soils. Soils that are stable would generally have strong aggregation, lower bulk density and higher void ratios. These properties contribute to soil water characteristic where well aggregate soils would have high water contents at saturation.

On the other hand, compacted soils would have lower water contents at saturation due to smaller void ratio and higher bulk density. Compacted and well aggregated soils also have different pore size distributions. Compacted soils have smaller

proportion of large pores, higher proportion of medium and small pores compared to those of well aggregated soils. Therefore, as the suction increases, the compacted soils would drain at a slower rate. These relationships are shown in Figure 3.3.

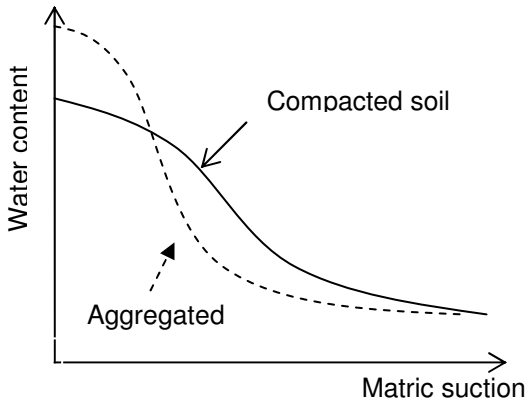


Figure 3.3: The effect of structure on soil water retention curves (Hillel 1971)

3.5.4 Methods for Measuring Soil Water Content

According to Singer and Munns (2002), soil moistures contents could be determined by the direct or indirect methods. The simplest direct measurement of soil water content is the gravimetric method, where the principle involves the measurement of water lost be weighing a soil sample before and after oven drying at 105 – 110 ºC. The resulted water content is presented in the percentage of water per 100 gram of oven dried soil, or as g/g (gram of water per gram of oven dried soil).

$$\text{Gravimetric water content} = \frac{water\_removed}{oven\_dry\_weight} \times 100\% \qquad \text{(g/100g)} \qquad \text{eq.3.3}$$

The indirect measurements of soil water content involves the use of equipments such as Neutron probe, gypsum blocks and Time domain reflectometry (TDR).

3.5.5 Methods for Measuring Soil Water Characteristic

Suction Plate Apparatus:

Suction plate consists of a water saturated, highly permeable porous ceramic plate that is connected to a water column terminating a reservoir. Different suctions are created by raising or lowering the water reservoir. This reservoir is open to the atmospheric and soil samples are placed onto the ceramic plate. When the water surface in the reservoir is at the same level as the top of the plate, the system is subjected to a zero-suction. Therefore, to apply a suction, the reservoir is lowered to a new level. Water will flow from the soil samples through the porous plate to the reservoir if suctions are applied to initially saturated samples. On the other hand, water will flow from the reservoir to the soil samples if they are initially dry. The samples are left to reach equilibrium at a particular suction, and then weighted to determine the gravimetric moisture content.

Another form of suction plate is the use of Haines apparatus where a Buchner funnel is used instead of a ceramic plate, and a burette is used instead of a water reservoir. This technique allows for the measurement of the volume of water taken up or drained from the soil at a particular suction. Both the suction plate and Haines apparatus are limited to the measurement of only a small proportion of the soil water characteristics. The systems are limited to the available space and practicability of lowering the water reservoir or burette (Hillel 1971).

Pressure membrane apparatus:

Pressure membrane apparatus can give the measurement of water contents corresponding to a matric suction ranging from 100 to 1500 kPa (1 to 15 bars). This system comes with ceramic plates that are designed with a particular pore size for the measurement at a specific pressure. Saturated soil samples are placed on a saturated ceramic plate in the chamber. The system is connected to the outside atmosphere by a water column. The chamber is pressurised to increase the matric suction on the soil samples. Water will flow from the soil samples to through the ceramic plate to the

chamber and will cease when the equilibrium is reached. The soil samples are then removed for the measurement of gravimetric moisture content.

3.6 Hydraulic Conductivity

3.6.1 Principal and Definition

Hydraulic conductivity (K) can be defined as the rate at which water passes through a soil material under unit gradient; it is the portionality factor in *Darcy's law* as applied to the viscous flow of water in soil. Therefore, it is the flux of water per unit gradient of hydraulic potential and depends on the intrinsic permeability of the medium and the fluid properties. Furthermore, the K in unsaturated soil decreases as the water content decreases (Gregorich et al. 2001).

The quantity of water flowing through a saturated column of soil can be expressed using

Darcy's law as: $q = \frac{Q}{At} = \frac{K_{sat}\Delta H}{L}$ eq.3.4

where: q is the flux (cm/min)

t is the time interval (min)

Q is the rate of water discharge (cm^3/min)

A is the cross sectional area of the soil column (cm^2)

K_{sat} is the saturated hydraulic conductivity (a soil property) in cm/min

ΔH is the hydrostatic pressure difference from the top to bottom of the column (distance from top of water to base of soil column) in cm.

L is the length of the soil column (cm)

$\frac{\Delta H}{L}$ is the hydraulic (potential energy) gradient

K_{sat} of a uniform soil is expected to remain constant over time if there is no rapid change in soil condition and gradient. The value of K depends on soil structure that includes the size and distribution of the soil pores and how well the pores are connected.

3.6.2 Factors Affecting the Hydraulic Conductivity

During unsaturated and saturated flow, the hydraulic conductivity is affected by various soil and water properties. Soil physical properties affecting K are total porosity, pore size distribution and tortuosity. On the other hand, water properties affecting K are its density and viscosity. These fluid properties are dependent on temperature. The flow rate of water in soil pores is proportional to the fourth power of the pore radius. Therefore, macropores with diameters > 0.04 mm contribute to most water movement in saturated soils. The presence of biopores created by roots and earthworms could significantly increase the value of K_{sat}.

Soil texture and structure have direct impacts on K_{sat} because of their influence on the size and distribution of pores. The effect of soil texture on K_{sat} is illustrated in Figure 3.4.

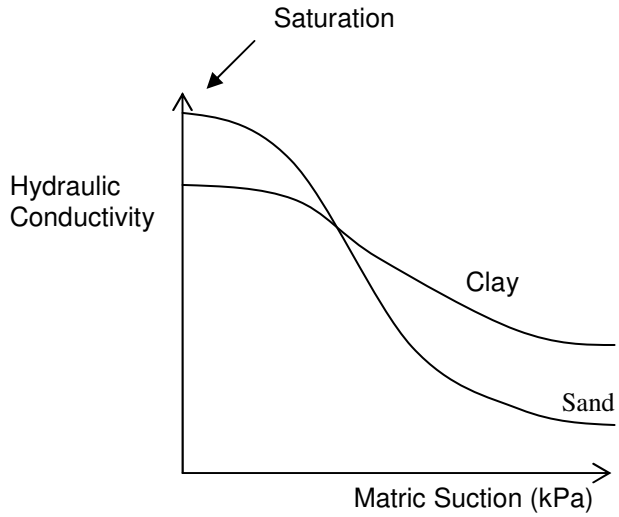


Figure 3.4: The effect of water potential on K of sand and clay soil (Hillel 1971).

Figure 3.4 shows the general relationship between matric suction and K of sand and clay soils. At or near zero matric potential in saturated soils, the sandy soil will have a larger K due to the fact that it has greater proportion of large, well connected pores. On the other hand, clay soil is dominated by small pores and high tortuosity. As the soil dries, its matric potential drops from zero (or matric suction increases), the large pores in sandy soil rapidly drain decreasing the value of K, while the predominance of small pores in clay soil still contributes to water flow. Therefore, K of the clay soil is higher than that of the sandy soil at low water potential (high matric suction).

Lastly, temperature could affect soil water movement through surface tension and vapour pressure of water. Generally, soil water movement is enhanced in the direction of decreasing temperature because temperature gradient gives rise to a potential gradient. Similarly, water vapour movement within soil is also enhanced in the direction of decreasing temperature.

3.6.3 Methods for Determining Soil Hydraulic Conductivity

Methods for measuring soil hydraulic conductivity include that of the field and laboratory methods. Available field methods are time consuming and require a relatively large quantity of water. Therefore, these methods may not be applicable for cracking clay soils. In field conditions, water entry and redistribution within soils take place in unsaturated condition. However, the laboratory measurements to simulate field conditions are complex and may not be possible. Thus, the measurement of soil saturated hydraulic conductivity (K_{sat}) under positive head is more common. The soil cores for this measurement could be under disturbed or undisturbed conditions. The disturbed cores are samples from standard preparation and packing to desired bulk density. On the other hand, the undisturbed cores should provide a good representation of the soil in-situ condition (Loveday 1974).

Chapter 4

Materials and Methods

4.1 Soils

4.1.1 Soils of Toowoomba

According to Thompson and Beckmann (1959), during the Tertiary Period, particularly in the late Oligocene to early Miocene (37-23 million years ago), there were volcanic activities in a number of areas, including Toowoomba. These activities resulted in basaltic flows to form the Great Dividing Range. The flows cooled down; deposited, and have undergone the process of weathering and erosion to provide the source material (Basalt) for the formation of extensive alluvial surfaces (level to very gentle inclined surfaces). Most of the soils in Toowoomba have developed into basaltic material although there are small isolated areas formed on sandstone, limestone and marl.

Dissection and erosion on the basalt and laterite surface have produced a variety of land forms which are grouped as follows:

(a) The Toowoomba Plateau, found around the city of Toowoomba and generally above the level of 609.6 m (2000 ft) contour;
(b) The Basaltic Uplands, occupies about three quarter of the Toowoomba area with the central portion through Wyreema and Westbrook;
(c) The Alluvial Plains, very extensive west of the Toowoomba sheet, but extend into up the valleys of creeks along the western margin;
(d) Steep Eastern Slopes of the Range, along the eastern edge of the range with a series of steep slopes due to intensive erosion by coastal stream.

A recent soil survey conducted by Biggs et al. (2001) provides considerable details of the soils in Toowoomba. This survey included information on soil mapping units, major attributes of the dominant soil, land form, the corresponding Australian soil

classification and areas in hectares. The properties of the Toowoomba plateau are summarised in Table 4.1 below:

Table 4.1: Soils of the Toowoomba Plateau (adapted from Biggs et al. 2001)

Mapping Unit	Major attributes of the Dominant soil	Landform	Australian Soil Classification	Area (ha)
Drayton	Moderately deep, neutral, red clay over basalt.	Hillslopes of gently undulating to undulating plains and rises.	Red Ferrosol	526
Kynoch	Deep, neutral, red, clay over basalt.	Hillslopes of gently undulating to undulating plains and rises.	Red Ferrosol	235
Nelson	Moderately deep to deep, neutral, brown, structured clays with ferro-manganiferous segregations.	Footslopes and drainage depressions of undulating plains and rises.	Yellow or Brown Ferrosol	303
Gabbinbar	Deep to very deep, snuff, neutral, red clay.	Hillslopes of gently undulating to undulating plains and rises.	Red Ferrosol	94
Middle Ridge	Deep to very deep, acid, red clays with ferric subsoils.	Hillslopes of gently undulating to undulating plains and rises.	Red Ferrosol	323
Ruthven	Deep to very deep, acid to neutral, red clay.	Hillslopes of gently undulating to undulating plains and rises.	Red Ferrosol	1 660
				Total area = 3141 ha

According to the data presented in the Table 4.1, it may be concluded that large proportion of the Toowoomba plateau is covered by Red Ferrosol. The red ferrosol accounts for 90% of the total plateau area.

4.1.2 Soil Used in Experiments

Disturbed and undisturbed soil samples from the top 15 cm was collected from the Agricultural Field Station Complex (Agricultural plot) of the University of Southern Queensland near Baker Street, Toowoomba. A soil profile description of the site conducted during September 2004 is given in Table 4.2. According to the key to soil orders, the soil was classified as a red ferrosol (Isbell 1996).

Table 4.2: Soil Profile Description of the Soil at the Agriculture Plot

Horizon	Depth		Colour	Field texture	Structure	Consistence	Field pH		Boundary
	Upper mm	Lower mm					pH	Depth mm	
A1	0	110	5YR4/6 yellowish	Clay loam	Moderate pedal	Very firm	5.5	60	
A2	110	400	5YR 3/3 dark reddish brown	Clay loam	Moderate pedal	Very firm	5.5	260	clear
B1	400	500	2.5YR 3/4 dusky red	Light clay	Strong ped Angular block	Very firm	6.0	450	gradual
B2	500	-	2.5YR 3/4 dusky red	Light clay	Strong angular blocky	Very firm	6.5	770	gradual
pH at 1:5 soil-water ratio					6.35 ± 0.012 (no. of replicates, n = 3)				
1:5 soil-0.01 *M* $CaCl_2$					5.43 ± 0.009 (n = 3)				
EC (µS/cm)					31± 0.33 (n = 3)				
Plastic Limit (g/g) or %					26.61 ± 0.26 (n = 5)				
Field Bulk Denstiy (g/cm^3)					1.19 ± 0.04 (n = 10)				
Emerson (1967) stability class					Class 5				

Soil samples collected from this site is expected to be a good representation of the soil types available in the residential areas of Toowoomba.

4.2 Preparation of Soil Cores

The experiment involved the use of both disturbed and undisturbed soil cores from the Red Ferrosol at the Agricultural Field Station of USQ. All soil cores had a dimension of 5.3 cm diameter and either 3 cm or 6 cm height. Soil cores with 3 cm in height were used mainly for the determination of soil water characteristics, whereas those with 6 cm height were used for the determination of saturated hydraulic conductivity of soil. Both brass and stainless steel rings of 5.3 cm ID (inner diameter) and of the required height (3 cm or 6 cm) were used to retain all soil samples. Soil samples retained in brass rings were used only for moisture or bulk density measurements, whereas those in stainless steel rings were used for hydraulic conductivity and leaching experiments to avoid corrosion from laundry water.

Three types of soil cores were used in all experiments to simulate soil conditions that might exist in garden beds of typical suburban residential houses in Toowoomba. Undisturbed field soil cores were used to represent soil condition in the back yard of residential house that is used for lawn and subject to regular traffic from mowing and occasional disturbance of the surface soil. Disturbed soil cores with light compaction (bulk density lower than the field core) and moderate compaction (bulk density similar to field cores) were used to represent two types of garden beds. Soil cores of low bulk density represented a recently prepared garden bed that uses the red soil as the landscaping material and had undergone little settlement, and those with moderate compaction represented an older garden bed which has undergone settlement and had not been disturbed for some time.

4.2.1 Field soil cores

Field soil cores of various dimensions were collected from the top 10 cm depth of relatively undisturbed site at the USQ Agricultural Station using a model 0200 soil core sampler (Soil Moisture Equipment Corp., USA). Stainless steel rings were locally fabricated to suit the sampler as inner sleeves of the sampling tube (Figs. 4.1-4.5) and for the preparation of disturbed soil cores.

Figure 4.1: Core sampler rings of inner diameter 5.3 cm and 1, 3 and 6 cm in height.

Figure 4.2: Core sampler accessories for insertion and removal of the sampling tube

Figure 4.3: Core sampler being driven into the ground using a drop hammer.

Figure 4.4: Removal of soil core with the retained soil sample from the ground.

Figure 4.5: One field soil core with 5.3 cm diameter × 6 cm height or two field soil cores with 5.3 cm diameter × 3 cm height could be obtained from this tube.

4.2.2 Field Bulk density and Water Content

In order to determine the bulk density required for disturbed soil cores, initial measurements of bulk density (BD) and water content of field cores were made with ten field soil cores (3 cm high). These cores were obtained from two depths: 2-5 cm and 5-8 cm. As in some of the experiments, soil cores of 6 cm height was used, these measurements of bulk density were used to determine if there was significant variation in soil bulk density with depth within the top 10 cm of soil. The bulk densities of these cores were measured according to the core method described in Loveday (1974), section 5-5 to 5-8.

After collection, each core was trimmed (Fig. 4.6) and its volume was estimated as follows. The volume of soil retained in the cylinder of 5.3 cm ID and 3 cm height was $\frac{\pi \times 5.3^2}{4} \times 3 = 66.19$ cm^3.

The dry mass of soil solids and the water content of all soil cores were determined by weighing the moist soil cores and then after drying them in an oven at 105-110 ºC for at least 24 hour or more followed by cooling in a desiccator. The following calculations were made to determine bulk density and gravimetric and volumetric moisture content of soil.

Calculations

Considering M_1 = wet mass of soil core (g),

M_s = mass of soil solids (g),

V_B = total volume of soil (66.19 cm^3),

D_w = density of water taken as 1.00 g/cm^3 with an error of 0.2% at 20ºC,

Bulk Density, $BD = M_s / V_B$	g/cm^3
Gravimetric moisture content, $MC_g = (M_1 - M_s)/ M_s$	g/g
Volumetric moisture content, $MC_v = MC_g.BD/ D_w$	g/cm^3

Figure 4.6: Field soil cores with 3 cm height used for the determination of field bulk density.

The calculations and results are shown in Appendix B. Average field bulk density within the top 10 cm was found to be 1.19 ± 0.04 g/cm^3. The field volumetric moisture content was 31.45 ± 1.10 % or 0.315 ± 0.011 cm^3/cm^3.

4.2.3 Paired T-test

As the field soil cores were obtained from two different depths, a paired t-test was conducted to verify if these cores had any significant differences in bulk density and moisture content. Paired t test is used when two samples are not independent but correlated. Soil depth 1 (2-5 cm depth) and 2 (5-8 cm depth) without a gap in between could be considered as paired samples because they arise from the same spatial location. Two tailed t-tests test the null hypothesis H_0 for a soil property that the difference between BD at depth 1 and at depth 2 = 0. If there were 5 paired measurements then degrees of freedom was 5-1 = 4. If the calculated value of (t-calculated) > tabulated value of t (t-table at P = 0.05 at n-1 degree of freedom), then H_0 would be rejected with the conclusion that the differences between BD is significant. However, if t-calculated is smaller or equal to t-table, then H_0 is accepted with the conclusion that the testing property is not significantly different.

All calculations were done in an Excel spreadsheet, the results of which are attached in Appendix C. This method of comparison was used for BD, WCg and WCv. For WC_g example in the above analysis, t stat (T) = -1.08182 and t-calc = 2.776; also that the probability P that T≤t-table was 0.34. As this value of P > 0.05, H_0 was accepted and it could be stated that there was no significant difference in WC_g with depth. The same conclusion was reached while testing for differences in BD and WC_v with depth.

Therefore, it was concluded that there was no significant difference in bulk density and water contents of the field soil cores from these two depths. Thus, they could be used interchangeably for various measurements throughout the experiments.

4.2.4 Disturbed soil cores

Disturbed soil samples from an area adjacent to field soil cores were collected to produce disturbed cores in the laboratory. Sufficient soil (in excess of 20 kg) was transported from the field to the laboratory and then air dried in large trays at a temperature below 40 ºC and finally sieved to less than 2 mm in diameter. Disturbed soil cores were packed to two levels of BD. These two BD reflected the bulk density of field soil as described previously. The disturbed cores with the low BD of 1.05 g/cm^3 were referred to as loose cores, and assumed to represent a recently prepared garden bed of a residential house using local soil. On the other hand, the disturbed cores with the higher BD of 1.20 g/cm^3 were referred to as compacted cores, and assumed to represent the soil of a residential garden that had been subjected to natural settlement.

To identify the amount of wet soil needed to achieve the desired compaction and bulk density, air-dry moisture content of the sieved soil was measured using the procedure for determining air-dry moisture content as described in method 2A1 of Rayment and Higginson (1992). Soil wetter than the plastic limit (PL) is considered ideal for compaction and therefore, soil at a moisture content of 1.2 times the plastic limit (PL) was used for packing. The plastic limit of the soil was determined using method 31-3.5 as described in Black et al. (1965, part 1). The calculations for air dry moisture content and plastic limit and the amount of wet soil needed for the preparation of disturbed cores and its derivation are in Appendix D.

4.3 Soil pH and EC

Hydrogen ion concentration in soil (pH) and electrical conductivity (EC) of the soil was measured using the method 4A1 and 4B1 of Rayment and Higginson (1992). Twenty gram of air dry soil (<2 mm fraction) was mixed with 100 ml of deionised water in a 250 ml beaker to prepare a 1:5 soil-water suspension. The soil water mixture was stirred every five minutes for an hour (equivalent to mechanical shaking in a closed container for an hour). A similar suspension was prepared by mixing equivalent amount of soil with 0.01 M $CaCl_2$ solution at a ratio of 1:5. There were three replicates for each type of suspension. A pH meter (TPS model MC80) and EC meter (TPS Model MC84) equipped with appropriate electrodes were calibrated following the manufactures instructions and buffer or standard salt solution. After satisfactory calibration, pH of each suspension was measured ensuring that electrodes were well immersed in the suspension and following stirring of the suspension until a steady reading was obtained. EC of the soil water suspension was also measured in a similar manner. Measured values of pH and EC are shown in Table 4.3.

Table 4.3: The soil pH and EC

	1:5 soil/water		1:5 soil/0.01M$CaCl_2$
Replicate	pH	EC (µS/cm)	pH
1	6.35	30	5.44
2	6.33	31	5.43
3	6.37	31	5.41
Average	6.35 ± 0.012	30.67 ± 0.333	5.43 ± 0.009

* 1dS/m = 1000 µS/cm

4.4 Soil Water Characteristic

Soil water characteristic is the relationship between volumetric soil moisture content and its corresponding matric suction for a range of water content or matric suction. This relationship is subject to hysteresis, i.e. the relationship is different if the soil is wetted to a matric suction or dried to the same suction.

4.4.1 Soil Samples

Soil samples for determining water retention curves consisted of 3 field core, 3 loose cores (disturbed cores with BD of 1.05 g/cm^3) and 3 compacted cores (disturbed cores with BD of 1.20 g/cm^3). The sample dimensions were 5.3 cm in diameter and 3 cm in height. The time for samples to reached equilibrium is expected to be proportional to the square of the sample hight (Dane & Topp 2002). Therefore, a sample height of 3 cm was practical in that it allowed the samples to be handled properly as well as minimised the equilibration time. Furthermore, cheese cloth, rubber band and ducting tape were used to prevent soils from falling out of the rings. One cm height collar of the same dimension (internal diameter) was placed on top of each soil core. Ducting tape was used to hold the tow rings together. The extra collar allowed the measurements and observation of swelling and vertical expansion of the soil samples. Their weights were recorded for further correction to the measured amount of water retained by soil.

4.4.2 Sample Wetting

Figure 4.7: Soil samples placed in a try to allow wetting of soil cores to saturation from the bottom of the sample.

Wetting, draining and weighing of soil cores were done by keeping the soil cores intact in their sampling cylinders. Dry cores could be saturated conveniently by capillarity. Soil cores were placed on the lattice as shown in Figure 4.7. Water was added to about 0.5 cm higher than the lattice level. These cores were left overnight to ensure that adequate time was given for saturation and to allow soil to reach an equilibrium water content at saturation. Furthermore, the top of each core was marked with three points 'A', 'B' and 'C'. These points were used as the reference points to measure any expansion or contraction of the soil cores during wetting and draining process.

4.4.3 Use of Suction Plate Apparatus

A suction plate apparatus was used to determine soil moisture at various matric suctions using the procedure adapted from the method 6-30 of Loveday (1974) where the same set of core samples was equilibrated to a range of matric suctions. These matric suctions were applied by raising the porous ceramic plate to create gravitational head difference of -0.1, -0.3, -0.5, -0.7 and -1.0 m from a free water surface that corresponded to the applied suction of -1, -3, -5, -7 and -10 kPa at the bottom of soil samples, respectively.

Initially saturated cores were placed on the plate at the lowest suction (0 kPa) and left for a minimum of 24 hours as shown in Figure 4.8.

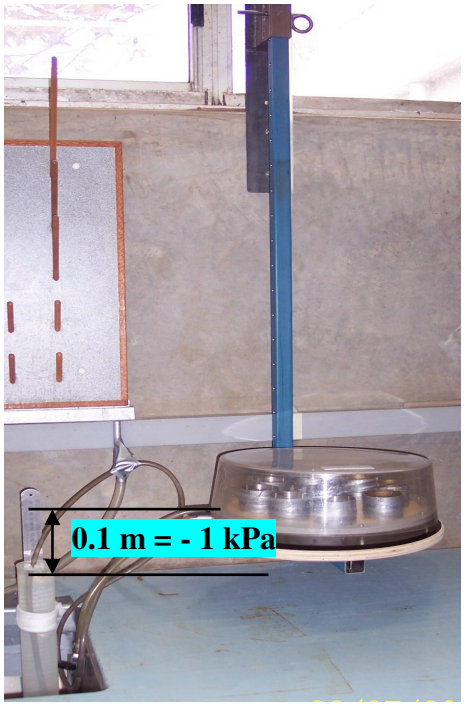
Figure 4.8: Initially saturated soil cores placed on the porous ceramic plate at zero suction.

After 24 h equilibration period, the cores were carefully transferred to a covered container to prevent evaporation. The cores were handled carefully during transfer to ensure that no soil was lost or removed. The weight of each core was then taken on an electronic balance (±0.01 g) to determine the wet weight at that particular suction. Any vertical expansion of the soil within the core was measured at the three points (A, B and C). The cores were then returned to the plate by first sprinkling a few drops of water on the plate to ensure good contact. Next, the suction was set to the next chosen level (higher value) to determine the moisture content at the new suction after it was drained to reach equilibrium. The process of draining and weighing was repeated until all samples reached equilibrium at the highest desired suction of 1 m or 10 kPa (see Figure 4.9).

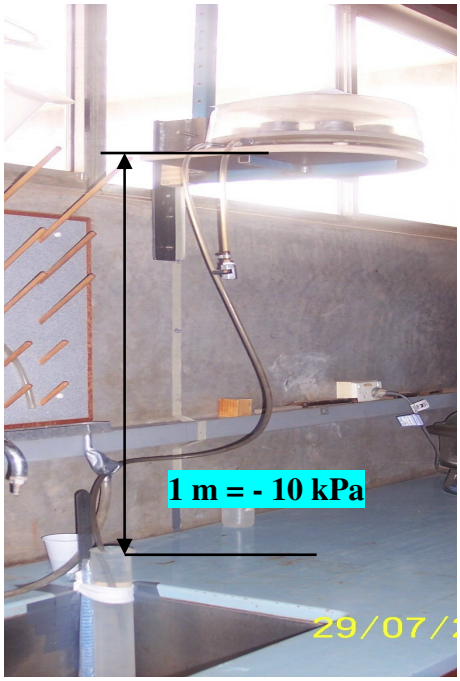
Data on moisture contents for this range of suction (0-1 kPa) obtained by draining of saturated cores gave the **desorption** part of the soil water characteristic curve. The **sorption** part of the curve was obtained by applying the wetting process to the same soil cores. This process was conducted by lowering the plate down from the highest suction (1 m) to the lowest suction (0 m) and repeating the procedures described for desorption.

After completing all measurements, soil cores were transferred to aluminium containers and subsequently placed in an oven set at 105 ºC to determine their water contents and bulk densities.

The calculations on soil water characteristic are given in Appendix E.
Calculation method used for soil cores is given below.



(a)



(b)

Figure 4.9: Soil cores equilibrated to 1 kPa suction (left figure), and 10 kPa suctions (figure on right).

4.5 Saturated Hydraulic Conductivity of soil

4.5.1 Soil Samples and Irrigation Scenarios

Soil samples used for the determination of saturated hydraulic conductivity (K_{sat}) consisted of four sets of soil cores. Each of the four sets consisted of three cores: one field, one loose and one compacted core. All soil cores were prepared using cheese cloth, filter papers, extra rings (that acted as 1 cm high collar on top of each soil core), rubber bands and ducting tape as shown in Figure 4.10.

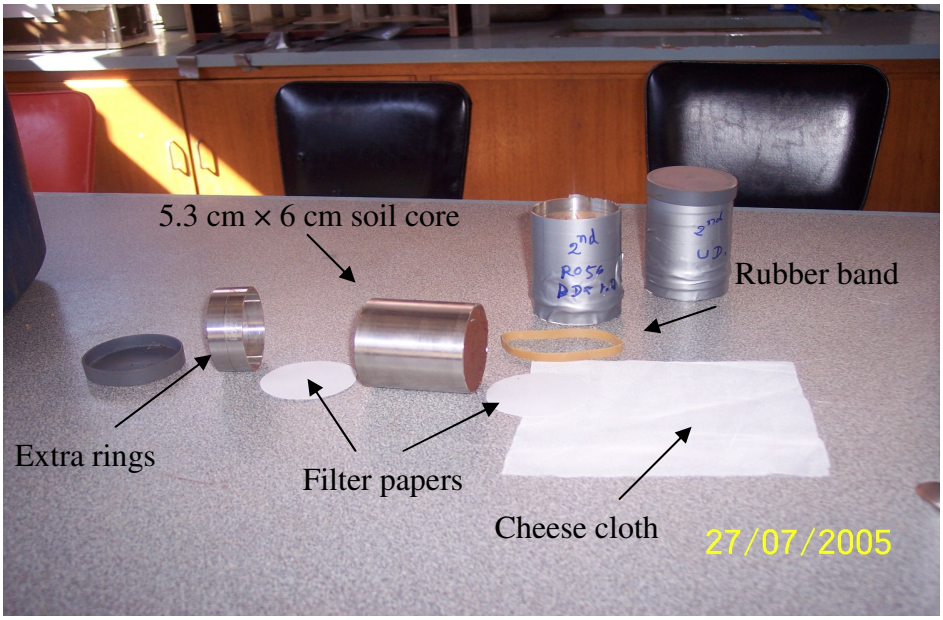


Figure 4.10: Soil core preparation for determining Ksat.

Two scenarios were used for the experimental processes. The first scenario was to apply tap water (common/current irrigation practice) or laundry water (alternative irrigation practice) to the unsaturated soil cores. This scenario involved surface application of irrigation water on the initially moist or unsaturated soil cores to represent common practice in irrigation of lawns and gardens in residential areas. This type of irrigation of lawns and gardens is commonly practiced when the soil is relatively dry after losing substantial amount of moisture though evapotranspiration. The second scenario was to apply laundry water as an automated irrigation event on saturated soil cores to represent a situation when the soil had become saturated due to rainfall prior to the irrigation event.

4.5.2 Leaching of soil cores with a Constant Head Device

A constant head device was used to apply all irrigation scenarios, measure saturated hydraulic conductivity by measuring drainage flux and collect drainage water as leachate for subsequent measurements. Darcy's law for saturated flow of water (eq. 3.4) was used to estimate saturated hydraulic conductivity of soil from the measurement of water conducted through the soil column over time and subsequent

identification of steady state values of water flux. This steady state could be approximated by observing the rate of change in the amount of water conducted over time (flux in cm/min). A plot of water flux against time was used to identify steady state, but as most data collection involved volume measurement of drainage water at fixed time intervals, steady state could be judged from the constancy of volume over time because other parameters remained reasonably constant throughout the data collection period. The last four readings of flux were averaged and used for the estimation of K_{sat}.

According to the equation 3.4, for vertical flow of water in a saturated soil of depth (L) with a depth of ponded water (Hp) on top of soil creates the pressure head Hp and water flow is due to a combination of pressure head and gravity head and the flux is directly proportional to hydraulic head difference as shown below in the diagram with calculations below and explanations.

Hydraulic head difference (ΔH) = Total head at inflow – Total head at outflow
= (Hp + L) – 0
= Hp + L

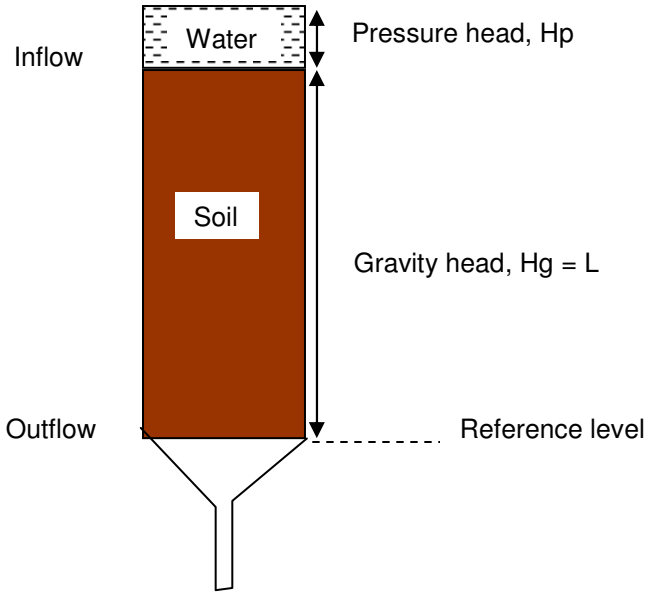


Figure 4.11: Schematic of the apparatus for the constant head method.

Darcy's law states that: $q = \frac{Q}{At} = \frac{K_{sat}\Delta H}{L}$,

where, q = water flux (cm/ min)

t = time interval (min),

Q is the rate of water discharge (cm^3/min)

A is the cross sectional area of the soil column (cm^3)

K_{sat} is the saturated hydraulic conductivity (a property of the particular soil)

ΔH is the hydrostatic pressure difference from the top to bottom of the column (distance measured from top of water to the bottom of soil column) in cm.

L is the length of the soil column (cm)

$\frac{\Delta H}{L}$ is the hydraulic (potential energy of water) gradient

In order to measure hydraulic conductivity using a constant head of water, all prepared soil cores were held secured over a bench at some height to allow a funnel and a measuring cylinder to be placed under each core using a set of clamps as shown in Figure 4.12.

An upturned 250 ml volumetric flask filled with tap water or laundry water (depending on the experimental scenario) was placed at 1 cm height over the top of the soil surface to act as a constant head water supply device, such as a Mariotte bottle. The pressure head was maintained within 1± 0.15 cm. Some amount of water from the constant head device was used for saturation of soil core and subsequently to measure water discharge from the soil core via funnel at five minute intervals with a measuring cylinder. Leaching of cores continued until the steady state was reached - this usually took one to two hours.

Figure 4.12: The constant head apparatus for Ksat measurement.

A number of 100 ml measuring cylinders were used to separate the collected leachate for further measurements of pH and EC and calculations of pore volumes of leachate collected.

Detailed records of discharge over five minutes time intervals and related estimates of K_{sat} are given in Appendix F. A sample calculation is shown below.

For a compacted core in the first set of cores, the steady state value of discharge was 10 cm^3. Therefore, $flux = \frac{Q}{At} = \frac{10cm^3}{(\frac{\pi \times 5.3^2}{4})cm^2 \times 5\,\min} = 0.091cm/\min$, and

$$K_{sat} = \frac{qL}{\Delta P} = \frac{0.091cm/\min \times 6cm}{7cm} = 0.078cm/\min = 46.8mm/h\,.$$

The pH and EC of the collected leachate were measured using pH and EC meters as described before for soil water suspensions. These values could be plotted against their corresponding pore volumes of drainage water to investigate the variation in the quality of leachate if the soils were irrigated over a period of time. Pore volume of water was estimated from soil pore space as described below.

$$\%PoreSpace = 100 \times \frac{ParticleDensity - BulkDensity}{ParticleDensity}$$

As the compacted core example used here had a BD of 1.188 g/cm^3 and assuming that the soil has a particle density of 2.65 g/cm^3

$$PoreSpace = 100 \times \frac{2.65 g/cm^3 - 1.188 g/cm^3}{2.65 g/cm^3} = 55.16\%$$

As the soil core had a diameter of 5.3 cm and 6 cm height, the volume of the core was $(\frac{\pi \times 5.3^2}{4}) \times 6 = 132.38 cm^3$.

Therefore, one pore volume of drainage water was equal to $\frac{55.16 \times 132.38 cm^3}{100} = 73 cm^3 = 73 ml$.

The bulk densities and pore volumes of all soil cores used in this experiment are given in Appendix G.

4.6 Chemical Properties

Selected chemical properties of soil, tap water and laundry water were analysed with assistance from a commercial analytical laboratory (CASCO, Toowoomba), except the measurements of. pH and EC. The CASCO used standard methods in Rayment and Higginson (1992) for the analysis.

For chemical properties of soil, three replicate soil samples were used. Cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) were estimated from the results of these analyses. CEC was the measure of the readily

exchangeable cations neutralizing the negative charge of soil colloids and it is significantly influenced by clay mineral type and parent material.

Table 4.4 : Chemical properties of the soil samples

Parameter names		Soil sample replicates			Convert to meq/100 g					meq./100g ov-dry soil
***Total:**	**Units**	**A**	**B**	**C**	**A**	**B**	**C**	**Mean**	**SE**	
Moisture	%	10.2	10.2	10.3	10.20	10.20	10.30	10.23	0.03	
Calcium	mg/kg	2000	2100	2000	9.98	10.48	9.98	10.15	0.17	**11.18**
Sodium	mg/kg	28	35	26	0.12	0.15	0.11	0.13	0.01	**0.14**
Potassium , k	mg/kg	71	69	62	0.22	0.22	0.19	0.21	0.01	**0.23**
Magnesium	mg/kg	540	550	510	4.44	4.52	4.20	4.39	0.10	**4.84**
***Exchangeable:**								**Mean**	**SE**	
Calcium	meq/100g				10.20	10.42	9.52	10.05	0.27	**11.07**
Sodium	meq/100g				0.12	0.15	0.11	0.13	0.01	**0.14**
Potassium	meq/100g				0.18	0.18	0.16	0.17	0.01	**0.19**
Magnesium	meq/100g				4.48	4.62	4.24	4.45	0.11	**4.90**

According to Tan (1996), CEC = $\sum$ exchangeable cations in meq./100 g oven dry soil. Therefore, CEC is the sum of exchangeable bases (Na^++K^++Ca^{2+}+Mg^{2+}) plus exchangeable H^+ ions. However, CEC was approximated by summing of exchangeable bases only. Therefore, CEC = (0.14+0.19+11.07+4.90) = 16.31 meq./100 g. Using the value of CEC, ESP was calculated as follows.

$$\text{ESP} = \frac{exchangeable\_sodium}{CEC} \times 100 = \frac{0.14}{16.31} \times 100 = 0.86\%$$

The leachate samples collected during hydraulic conductivity measurements for three treatments (field, loose and compacted cores) using tap water and laundry water were also analysed for the concentration of Ca, K, Mg and Na in irrigation and drainage water. These data will be presented in results section with the calculated values of sodium adsorption ratio (SAR) to compare the effects of irrigation with two types of water on the quality of drainage.

Chapter 5

Results and Discussions

As most of the experiments conducted in this project was based on one soil, important properties relevant to these experiments are discussed at the first instance.

5.1 Properties of the Experimental Soil

5.1.1 Physical and Chemical Properties

The soil used for all experiments is classified as a Red Ferrosol (Isbell 1996). The undisturbed soil in the field had a bulk density of 1.19 ± 0.04 g/cm^3 (n = 10) with an average pore volume (porosity) of 55.15 ± 1.43%. According to Rycroft and Amer (1995), non-swelling soils usually have a porosity ranging from 30-60%. In this section, numbers shown with '±' sign after a mean value indicate standard error (SE). At the time of sampling, this soil had a field volumetric moisture content of 0.315 ± 0.011 cm^3/cm^3 and a plastic limit of 26.61%. Details of these results are given in Appendix B. This soil is slightly acidic with an average pH of 6.35 ± 0.012 at 1:5 soil-water ratio, and 5.43 ± 0.009 for a similar 1:5 ratio of soil:0.01M$CaCl_2$ solution. The soil had an EC value of 31 ± 0.33 µS/cm when it is measured at a soil-water ratio of 1:5. Furthermore, the cation exchange capacity of the soil was16.31 meq/100 g which indicate that the main clay mineral of this soil could be Illite.

In general, the high values of CEC indicate the high clay content of the soil. CEC values of the heavy clacking clay (Vertosols) are reported to range between 20 and 80 meq/100 g of soil with the lower values being common in clays of the arid land (Hubble 1984). Ferrosols have lower clay content than Vertosols and as a result, they have lower values of CEC and lower susceptibility to cracking and swelling. In addition, the type of clay mineral associated with Vertosols is commonly

Montmorillonite type of clay that contributes to high CEC and swelling and shrinkage behaviour not common to Ferrosols.

5.1.2 Exchangeable Sodium Percentage and Aggregate Stability

According to Hubble (1984), clay soils having high sodium contents are prone to swelling and dispersion in which reduces their permeability and saturated hydraulic conductivity. When the clay soils have an ESP value greater than 5%, their saturated hydraulic conductivity is normally lower than 1 mm/h. The soil used in the experiments had an exchangeable sodium percentage (ESP) of (0.86 ± 0.061)% and calcium was the dominant cation. However, dispersion can still occur in soils of low ESP value if the soil receives water with sufficiently low salinity. Thus, the salinity of the infiltrating water has be less than 200 to 400 µS/cm to cause soils with low ESP and dominated by calcium to disperse. Field soil is likely to experience this condition under the action of rainfall (Rycroft and Amer 1995).

Aggregate stability measured for this soil during September, 2004 showed the soil to have a *class 5* aggregate stability using the key to Emerson's aggregate stability index (1967). This index gives key features to classify soil aggregate stability from *class 1 (complete dispersion)* to *class 8 (no swelling and slaking)*. Class 5 indicates that there is no dispersion but only slaking when the dry aggregate is immersed in water. Furthermore, when the soil is remoulded at water content equivalent to field capacity and immersed in water, the soil shows no dispersion in the absence of carbonate and gypsum. However, this soil exhibited some dispersion at 1:5 soil-water suspension.

Measurements of vertical swelling recorded during the soil water characteristic measurement are estimated to be 0.022 ± 0.023 mm over a soil column of 30 mm. This average expansion of about 0.07% was relatively small. However, most of the expansion occurred when the soil cores were brought to saturation. Furthermore, most contraction occurred during the first few days of applying low suctions. The

recorded data on vertical swelling and shrinkage of the soil cores is given in Appendix H.

5.2 Soil Water Storage

5.2.1 Field Capacity

In soils with low permeability such as clay soils, a true field capacity does not exist in terms of the original definition, when field capacity is defined as the percentage of water remaining in a soil 2 or 3 days after being saturated and experiencing free drainage. Therefore, field capacity of the clay soil was taken as the moisture retained after applying a matric suction of 33 kPa to the saturated cores for 48 hours. Mean values for field capacity with SE are shown in Table 5.1 for various types of cores used in experiments and comparisons are made in Figure 5.1.

Table 5.1: Moisture retained at field capacity (-33 kPa) for various cores. Both gravimetric water content (WC_g) and volumetric water content (WC_v) are shown.

Core treatment	Field	Loose	Compacted
wc_g (g/g)	0.299 ± 0.015	0.331 ± 0.010	0.352 ± 0.012
wc_v (cm^3/cm^3)	0.361 ± 0.015	0.348 ± 0.010	0.424 ± 0.014

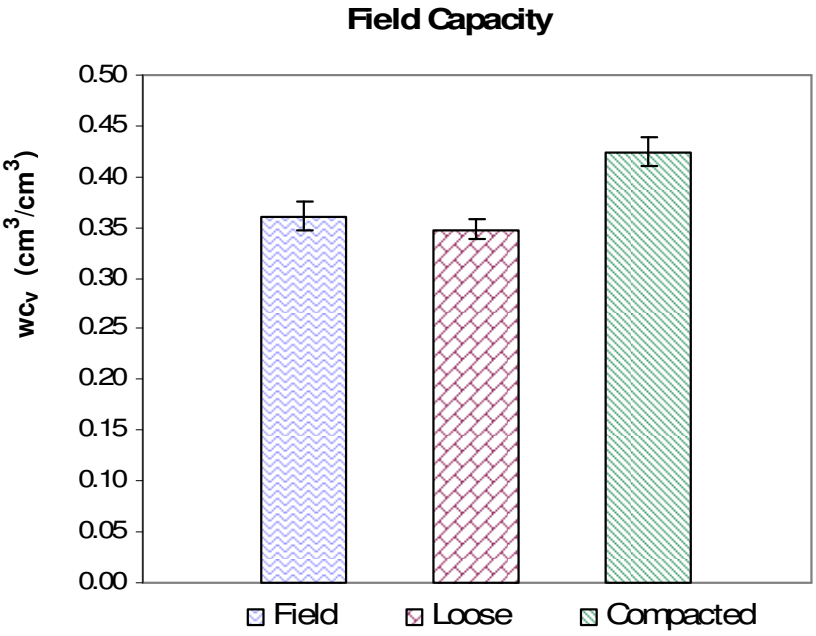


Figure 5.1: Volumetric water content (WC_v) at field capcity for three soil core treatments. Vertical lines over mean values indicate ± SE.

In general, the soil had an average water content of 0.38 cm^3/cm^3 at field capacity with the compacted cores retaining significantly more water at field capacity (0.42 cm^3/cm^3) that was about 20 % higher than those of the field and loose cores. These results illustrate the effect of pore size distribution on the soil water retention. Compacted cores with higher bulk densities than the loose cores might be expected to have a larger proportion of micropores allowing more water to be held at field capacity. Higher water retention in compacted cores compared to field cores at similar bulk density could be due to the lack of root channels likely to be present in undisturbed soils near the surface.

These results also show that the compacted soil is not likely to drain as freely as the other cores. it is also expected that plants will find it difficult to extract moisture from the compacted soils, especially when the soil is drying (Hillel 1971). In addition, results show that there is no significant difference in water contents of the field and loose cores at field capacity. Thus, one likely explanation that these two core treatments may have similar porosity and pore size distribution.

5.2.2 Soil Water Characteristic

Variation in volumetric soil moisture content at a range of matric suctions (0-10 kPa) is shown in Table 5.2 for various treatments. The relationship between moisture and suction plotted as soil water characteristic curves for various treatments are shown in Figure 5.2. Both data are shown for drainage (desorption) starting with saturation to increasing suction and for wetting (sorption) starting with an initially moist soil (10 kPa) to saturation.

Table 5.2: Volumetric moisture contents at various suctions

Treatments	Field Cores		Loose Cores		Loose Cores	
Suction - kPa	WC_v (cm^3/cm^3)	SE	WC_v (cm^3/cm^3)	SE	WC_v (cm^3/cm^3)	SE
0	0.535	0.013	0.594	0.006	0.541	0.004
1	0.478	0.022	0.573	0.007	0.533	0.003
3	0.429	0.021	0.446	0.011	0.500	0.003
5	0.402	0.019	0.401	0.013	0.479	0.010
7	0.391	0.017	0.382	0.015	0.459	0.021
10	0.378	0.014	0.365	0.013	0.454	0.013
7	0.382	0.021	0.353	0.009	0.436	0.013
5	0.388	0.024	0.355	0.010	0.440	0.012
3	0.401	0.021	0.365	0.014	0.446	0.010
1	0.424	0.023	0.417	0.019	0.484	0.012
0	0.526	0.013	0.593	0.005	0.538	0.006

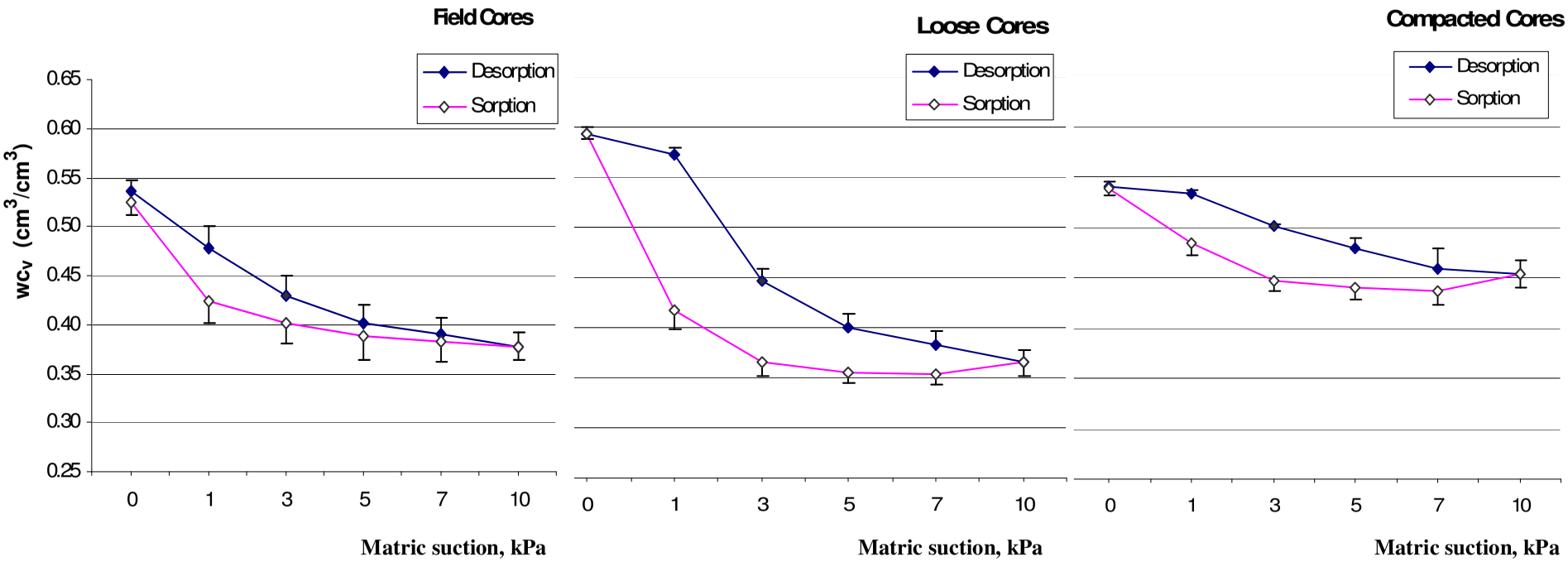


Figure 5.2: Soil water characteristic curves (relationship between volumetric moisture content, WC_v and matric suction) for the three soil treatments

In general, these curves show that all three treatments retained more water during drainage (desorption) than during wetting (sorption). The difference in water content between desorption and sorption (Fig. 5.2) was substantially smaller in field cores than for loose or compacted cores. According to Figure 5.2, the saturated water contents corresponding to the suction at saturation or near zero is related to the total porosity and void space of the soils. The loose treatment with a relatively higher porosity indicated significantly higher water content at saturation than the other two treatments. The pore volume and saturated water content of each treatment are presented in Table 5.3. In addition, the compacted cores retained more water than the other cores as the suction increased and the reasons could be the pore size distribution as previously discussed in section 5.2.1. The combined data on field capacity at 33 kPa suction and also for 0-10 kPa suction showed that compacted cores have a smaller proportion of large pores that drains easily. As a result, these drained at a lower rate compared to the field and loose cores.

As the loose treatment represents a recently prepared garden bed or lawn in a residential area in the Toowoomba city area, plants and other vegetation are likely to have more available water at high suctions compared to the older garden beds that has been subjected to natural settlement.

Table 5.3: Pore volume (porosity) and water content at saturation

5.3 × 3 cm cores for water characteristic measurement			
Treatment	**BD (g/cm3)**	**Pore volume (%)**	**WC_V at saturation (cm3/cm3)**
Field	1.21 ± 0.037	54 ± 1.4	0.54 ± 0.013
Loose	1.05 ± 0.001	60 ± 0.03	0.6 ± 0.006
Compacted	1.205 ± 0.001	54.5 ± 0.05	0.54 ± 0.004

5.3 Saturated Hydraulic Conductivity (K_{sat})

5.3.1 K_{sat} of Initially Moist or Unsaturated Soil

A summary of K_{sat} values for soil treatments under the first irrigation scenario is shown in Table 5.4 and presented graphically in Figure 5.3. From the graph and the table, it can be seen that the loose soil had the highest value of K_{sat} when the unsaturated cores were infiltrated by tap water. K_{sat} values were generally in the order loose > field > compacted. When these unsaturated cores were infiltrated with laundry water, the values of K_{sat} decreased by an average of 90% compared to those with tap water infiltration. Most reduction with leaching by laundry water occurred for the loose cores where there was a 97% reduction in K_{sat} . The changes in water flux over time for these two leaching treatments are presented in Figure 5.4.

Table 5.4: Saturated hydraulic conductivity (Ksat) of the initially unsaturated soils.

Treatment	Field	Loose	Compacted
1. TW only	155.02	579.28	92.08
1. LW only	29.14	18.65	8.16

K_{sat} (mm/h)

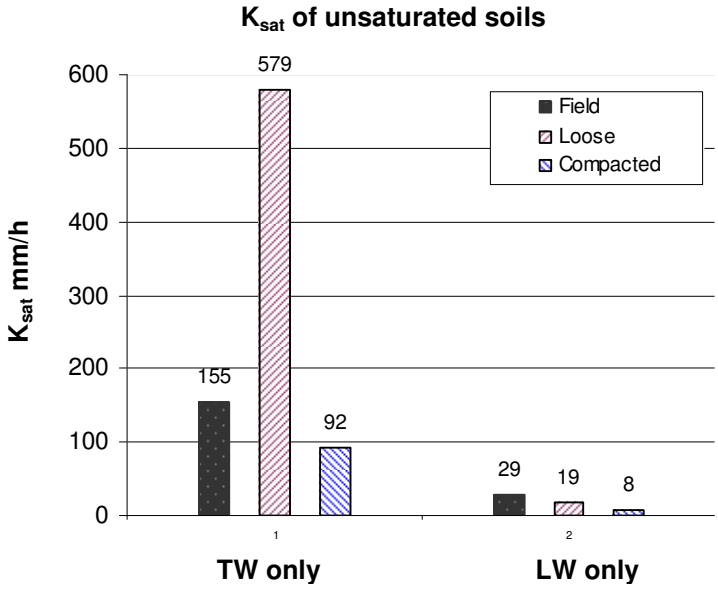


Figure 5.3: K_{sat} of the initially unsaturated cores after infiltration with tap water (TW) or laundry water (LW) using a constant head.

It is a common practice to irrigate gardens and lawns when they are dry having lost substantial amounts of moisture through evapotranspiration. If these initially unsaturated lawns and garden beds are irrigated with laundry water, the average conductivity of laundry water in the soil would be about 19 mm/h. On the other hand, if these soils are subjected to rain or irrigated with tap water, the average conductivity would be about 275 mm/h. These observations are further supported by the details of water flux measurements (in Figure 5.4), which shows that application of laundry water results in significantly low fluxes (discharge over unit area) in all soil treatments. Therefore, laundry water must be applied at a relatively very low rate over a long period of time, especially when it is used to irrigate old garden-beds that are subjected to certain levels of compaction and settlement.

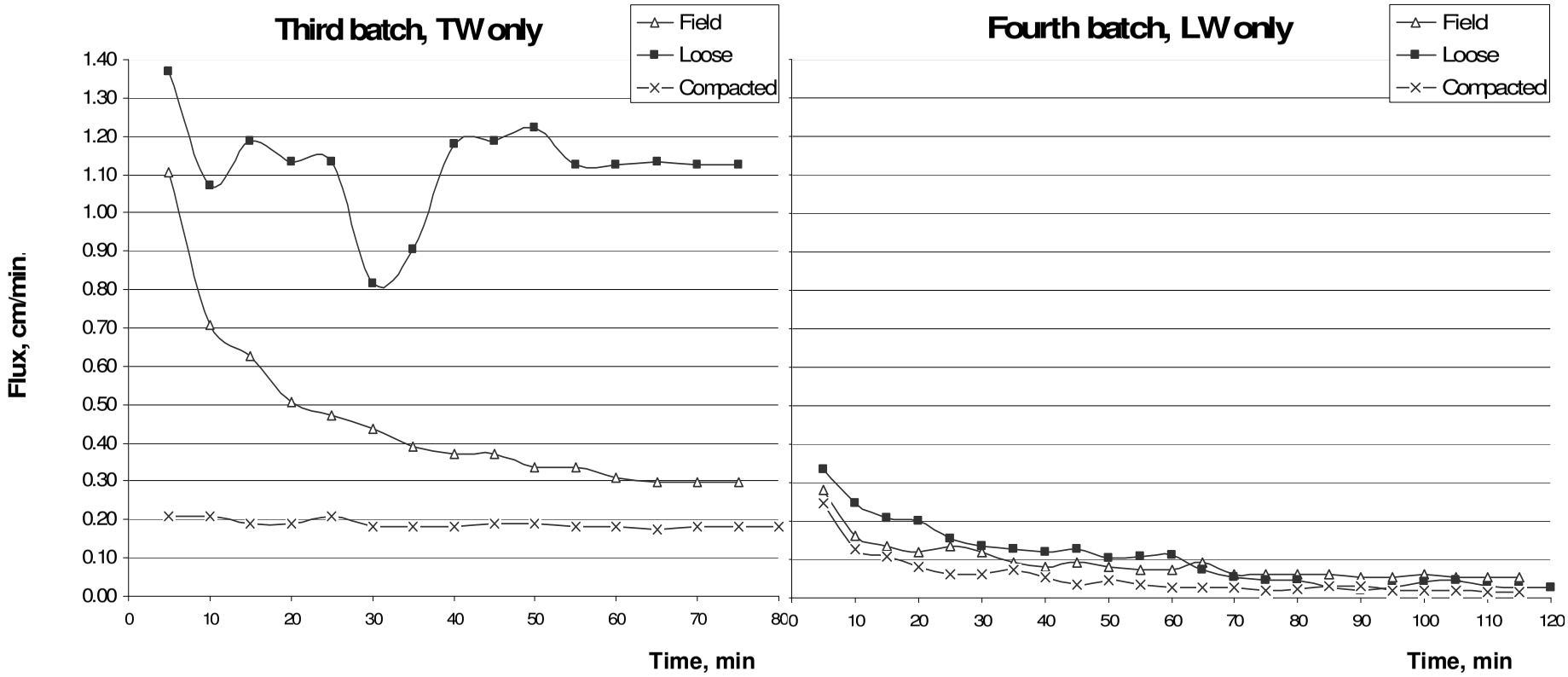


Figure 5.4: Variation in water flux over time for the initially unsaturated soils with a constant head water supply. For the third batch samples tap water (TW) was used while for the fourth batch samples laundry water (LW) was used.

5.3.2 K_{sat} of Initially Saturated Soils

In this irrigation scenario, two sets of soil cores were used for leaching. All cores were initially infiltrated twice with tap water before the application of laundry water to ensure that the steady state and saturation of cores have been reached. The resulting fluxes over time are shown in Figures 5.6 and 5.7. In these figures, each leaching treatment was separated by a time gap of 12 hours. These soil cores were kept at saturation during the time gaps. The leaching treatments included infiltration first by tap water, next repeated with tap water, laundry water, and finally followed by tap water. The discharges over time for these two batch of cores were more stable during the period of second tap water leaching than the first.

K_{sat} of each treatment is presented in Figure 5.5. The values of K_{sat} in this table are the average of those of the two sets of soil samples. From this figure, loose soil had the highest values K_{sat} of in all four leaching treatments. On the other hand, compacted soil has the lowest values K_{sat} of in all four leaching treatments. These results illustrate the effects of soil bulk densities, total porosity and pore size distribution on K_{sat}.

The results in Table 5.5 show changes in the values of K_{sat} over the four leaching treatments. Firstly, the application of second tap water caused a change in the value of K_{sat} by 16%. This means that changes in K_{sat} of the second tap water leaching would be in between -12% to 44% (with 65% confidence). Therefore, the values of K_{sat} could be either decreased or increased if the saturated soils are subjected to irrigation by tap water. These variations in K_{sat} could be due to structural changes associated with irrigation affecting pore connectivity, which means the pores involved in conduction of water during first irrigation are not necessarily conducting water during the second irrigation. There were substantial increases in K_{sat} of the disturbed soil conditions (33% for the loose treatment and 54% for the compacted treatment) when they were leached for the second time by tap water. Therefore, when there is a rain with multiple bursts, the residential garden beds and lawn would be able to conduct more water than the undisturbed suburban

backyards. In other words, there would be more runoff from the undisturbed urban soils than from the disturbed soils.

Table 5.5: K_{sat} of initially saturated soils.

Average: K_{sat} (mm/h) from the first and second batch samples						
Treatment	**Field**	**SE**	**Loose**	**SE**	**Compacted**	**SE**
TW	247.316	81	282.501	69	26.516	35
TW	150.429	59	375.308	171	40.794	0
LW	31.106	26	34.930	35	12.238	0
TW	12.055	11	18.867	10	3.060	1.2

Relative change in Ksat				
Treatment	**Field**	**Loose**	**Compacted**	**Average**
TW	-	-	-	-
TW	-39%	33%	54%	16%
LW	-79%	-91%	-70%	-80%
TW	-61%	-46%	-75%	-61%

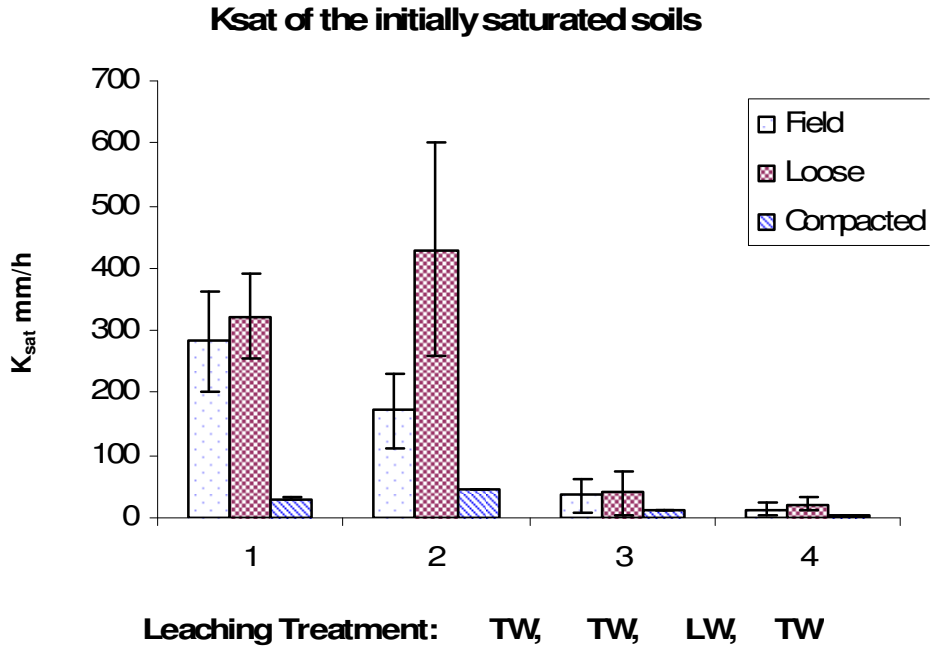


Figure 5.5: K_{sat} of the initially saturated soils.

When an already wet soil is irrigated by laundry water, K_{sat} is reduced by 80 ± 6 % (n = 3) compared to that if it was irrigated with tap water. Most reduction in Ksat occurred for loose cores (91%). Furthermore, the successive application of tap water caused a further reduction in K_{sat} of 61 ± 8 % (n = 3). According to Bouma et al. (1976), the main factor governs the K_{sat} values is the existence of small constrictions within the network of continuous macropores. Thus, changes in their size and connectivity due to swelling and dispersion can cause large changes in the values of K_{sat}. The laundry water used had a SAR value of 12.3 and an EC value of 0.752 dS/m. The dramatic reduction in K_{sat} of soil seen for irrigation with laundry water with high value of SAR could be due to the dispersion of clay causing pore blockage.

These results show that if laundry water is used for automatic irrigation and applied to garden beds or lawns in the backyards of residential houses which are already wet from a recent rainfall event, there would be a substantial decrease in the rate of water infiltration due to a dramatic reduction in the soils' K_{sat}. The situation can worsen if the soils saturated with laundry water receive further high intensity rainfall. The soils have an average K_{sat} of 12.95 ± 5.23 mm/h (n = 3) when tap water is infiltrated after laundry water. Therefore, rain fall with intensity greater than 18.2 mm/h (i.e. mean Ksat + SE) would generate runoff. This shows that when laundry water application in soils is followed by rain or application of potable water, significant reduction in K_{sat} is expected with very low rate of infiltration.

Lastly, Figures 5.6 and 5.7 show that the fluxes of laundry water usually start at relatively high values during the first ten minutes of leaching. Then water fluxes experience dramatic decrease during the next ten minutes. The leachate during the first ten minutes is relatively clean and suggests that tap water is being replaced by laundry water. More information about the behaviour of leachate is given in the next section.

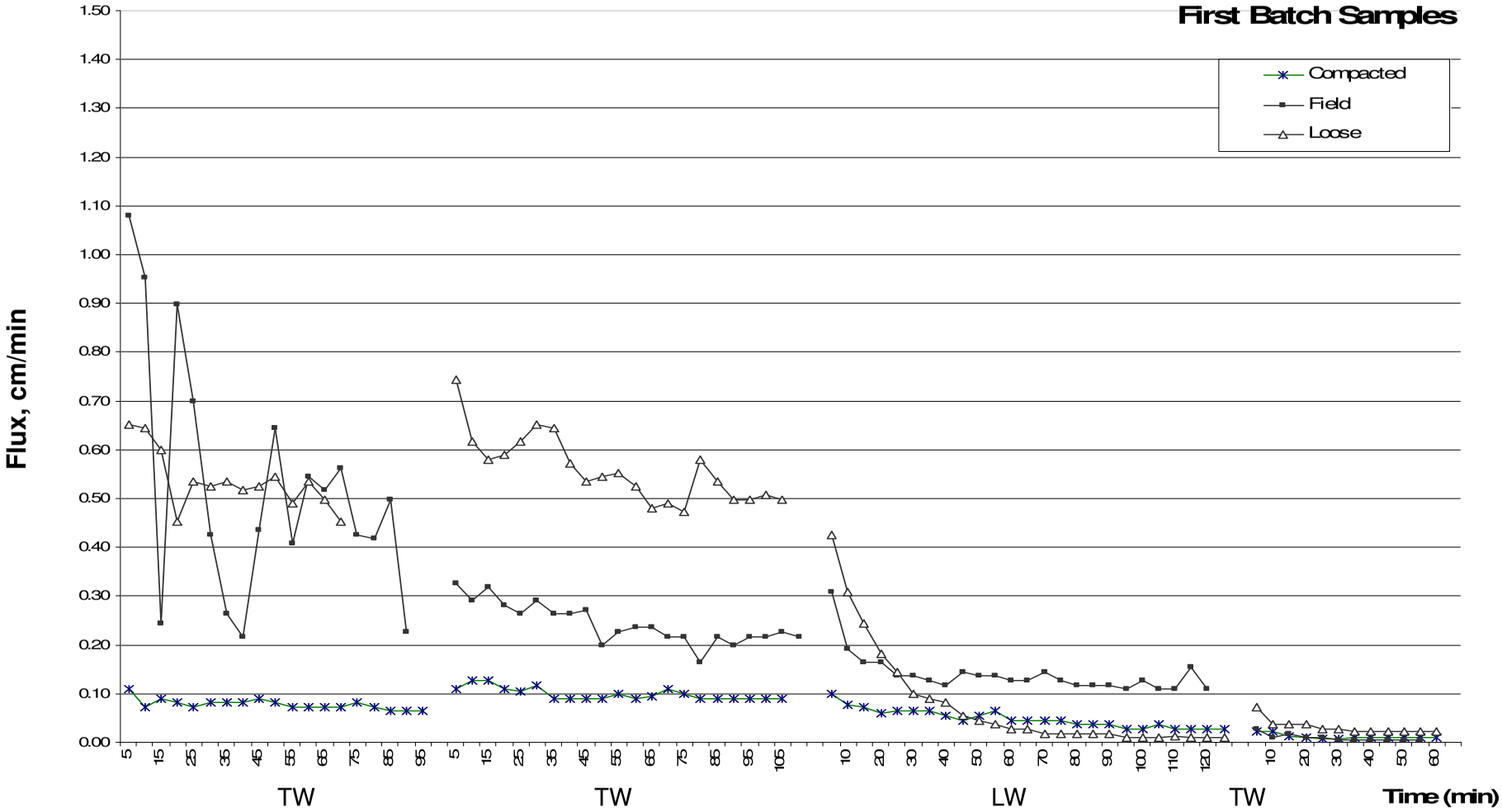


Figure 5.6: Water flux for the first batch of soil cores

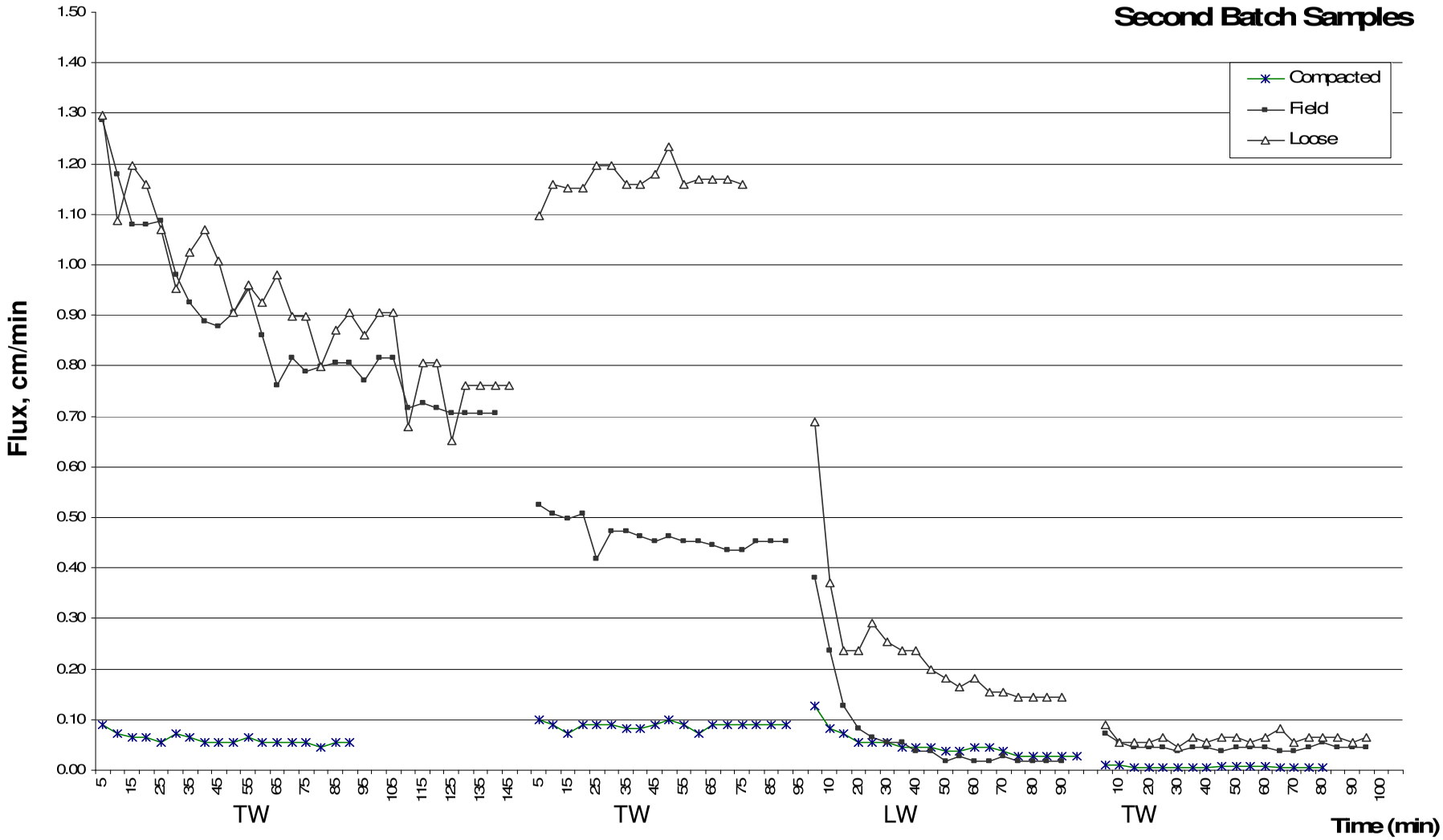


Figure 5.7: Water flux for the second batch of soil cores

5.4 pH, EC and SAR of the Irrigation water and Leachate

The tap water used in the experiment had a pH of 6.7 ± 0.007, EC of 388.33 ± 4.84 µS/cm, and SAR of 1.36 ± 0.03 averaged over three replicates (i.e.n = 3). The laundry water used for infiltrating soil core samples had a pH of 9.21 ± 0.003, EC of 752 ± 1.86 µS/cm, and SAR of 12.33. Therefore, this laundry water contained twice as much total salts as that of tap water. The laundry water had a sodium concentration of 5.74 meq/l compared to only 1.5 meq/l in tap water. Thus, laundry water had a very high value of SAR that could negatively affect soil properties. Generally, laundry water could have an average pH value of 9.5 ± 0.4, EC of 1207 ± 240 µS/cm, and SAR of 12.37 ± 1.7 over 27 replicates collected in Toowoomba city households (Lee MN, 2005, pers. comm., 15 Oct). The quality and changes in these properties of the leachate are discussed in the next sections.

5.4.1 Leachate from Initially Unsaturated Soils

Tap water leachate from the initially unsaturated soils had a pH of 5.9 ± 0.13, and an EC of 388 ± 6 µS/cm averaged over 15 replicates (i.e. n = 15). These replicates are the number of pore volumes at which the leachate were collected and measured. These properties of the tap water leachate were not significantly different from those of the original tap water. Figures 5.8 and 5.9 show the changes in pH and EC of the tap water leachate over several pore volumes of leachate collection. Figure 5.8 shows that the tap water leachate had pH values those are relatively stable over several pore volumes. The values of EC for the loose and compacted cores tend to decrease over pore volumes, while that of the field core remain relatively the same.

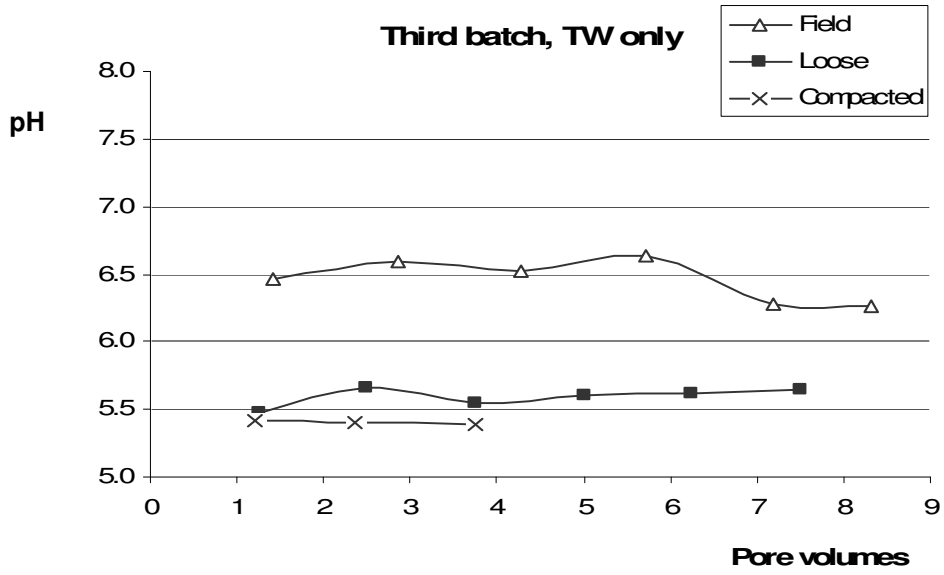


Figure 5.8: Changes in pH of the tap water leachate over serval pore volumes of leachate collection.

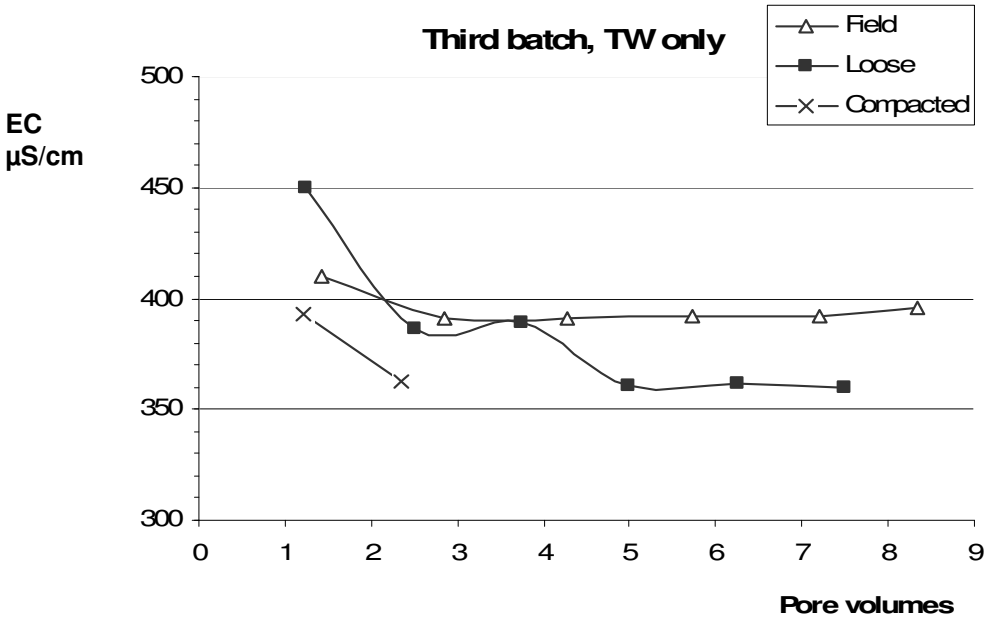


Figure 5.9: Changes in EC of the tap water leachate over serval pore volumes of leachate collection

The laundry water leachate from the initially unsaturated soils had a significantly higher pH of 7.13 ± 0.55, and higher EC of 725 ± 41.46 µS/cm (n = 15) than the leachate from tap water as shown in Figures 5.10 and 5.11. As the laundry water used for leaching had a pH of 9.2 and an EC of 752 µS/cm. Therefore, the irrigation of laundry water only on the initially unsaturated soil results in leachate whose pH is reduced but it contains salt similar to those of the original laundry water. This leachate also had a high level of soluble salts that might get transferred to soils at greater depths and in areas with shallow ground water (e.g. near creeks) it may contaminate ground water.

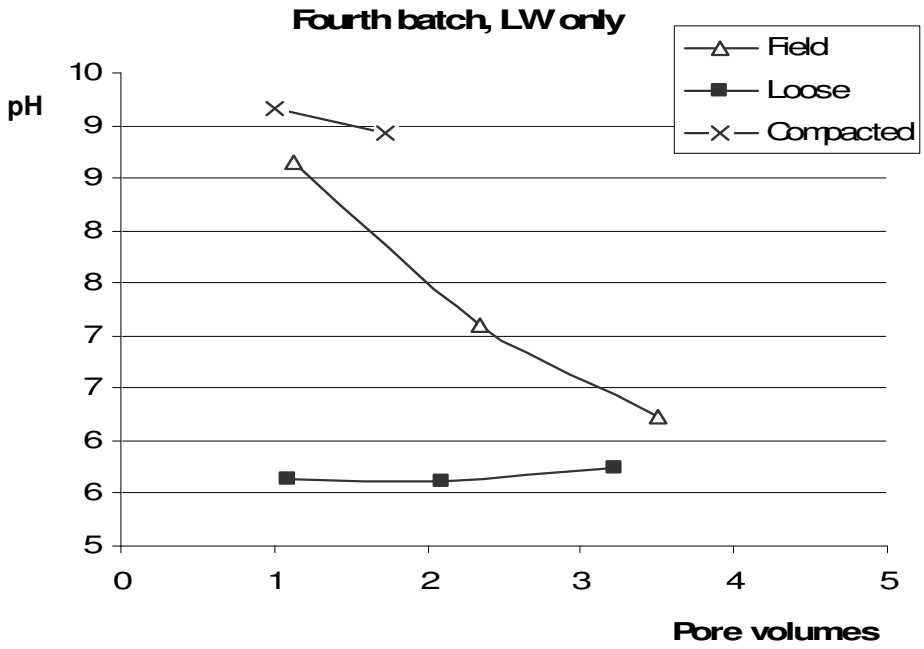


Figure 5.10: Changes in pH of the laundry water leachate over serval pore volumes of leachate collection.

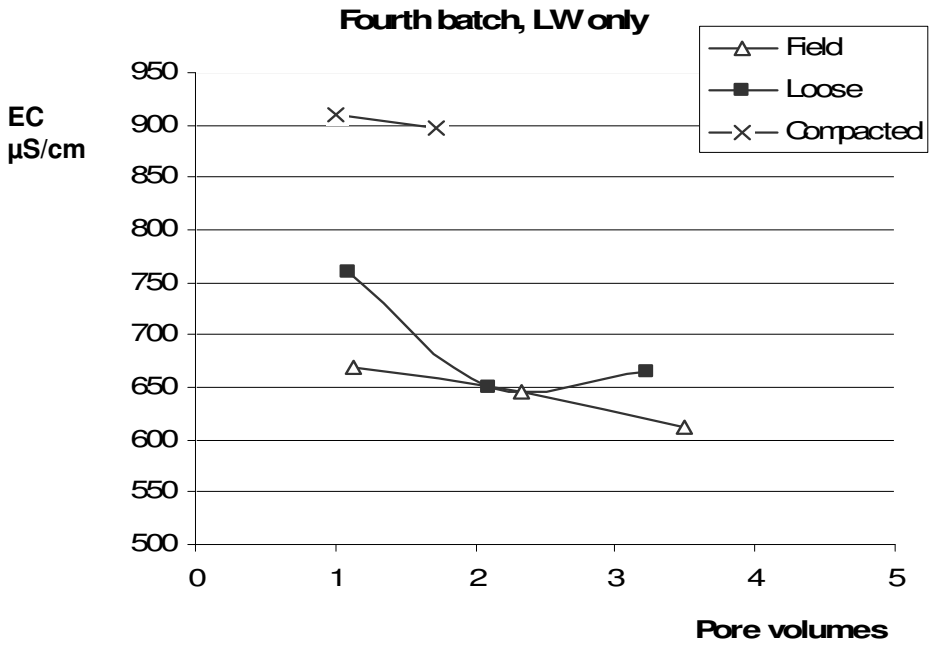


Figure 5.11: Changes in EC of the laundry water leachate over serval pore volumes of leachate collection.

5.4.2 Leachate from Initially Saturated Soils

The leachate with sequential application of tap water (TW) and laundry water (LW) using the first batch of soil cores had a pH of 6.32 ± 0.05 (n = 41) and EC of 357 ± 12 µS/cm (n = 41). The leachate from the second batch of soil cores had a similar pH and EC, 6.12 ± 0.05 (n = 53) and 353 ± 10 µS/cm (n = 53) respectively. These values were the means from averaging of the number measurements with respect to pore volumes and soil core treatments. The leachate from the first batch of soil cores was collected as 41 separate volumes for the measurement of pH and EC. Similarly, the leachate from the second batch of soil cores was collected as 53 separate volumes.

These values of pH and EC of the leachate were similar to that of the tap water used in the infiltration. Changes in pH and EC of these soils over the four leaching treatments are shown in Figures 5.12 and Figure 5.13. Measured values of pH and

EC for the leachate in various leaching treatments are separated by a gap to indicate change of irrigation water.

Figure 5.12 shows the changes in pH of the first and second batches of soil cores over pore volumes. Similarly, changes in EC of the four leachate treatments could be observed from Figure 5.13. The effects of laundry water application on the characteristics of the leachate are shown as the third application in the sequential application of water. From these graphs, it can be seen that the pH and EC of laundry water leachate was similar to those obtained when the soils were leached with tap water.

The application of potable water or rain after laundry water irrigation was presented in the fourth of sequential application water. Only a few measurements of pH and EC were done for this leachate (from the loose and field cores of the second batch of soil cores). The pH of this leachate was averaged to be 6.27 ± 0.12 (n = 4), and the EC was averaged to be 547 ± 27.8 µS/cm (n = 3). According to these values, the application of potable water or rain on soils that received laundry water (being wet by laundry water) would result in producing drainage water that has pH similar to that of tap water, but its EC would be increased by about 30% of the original tap water value.

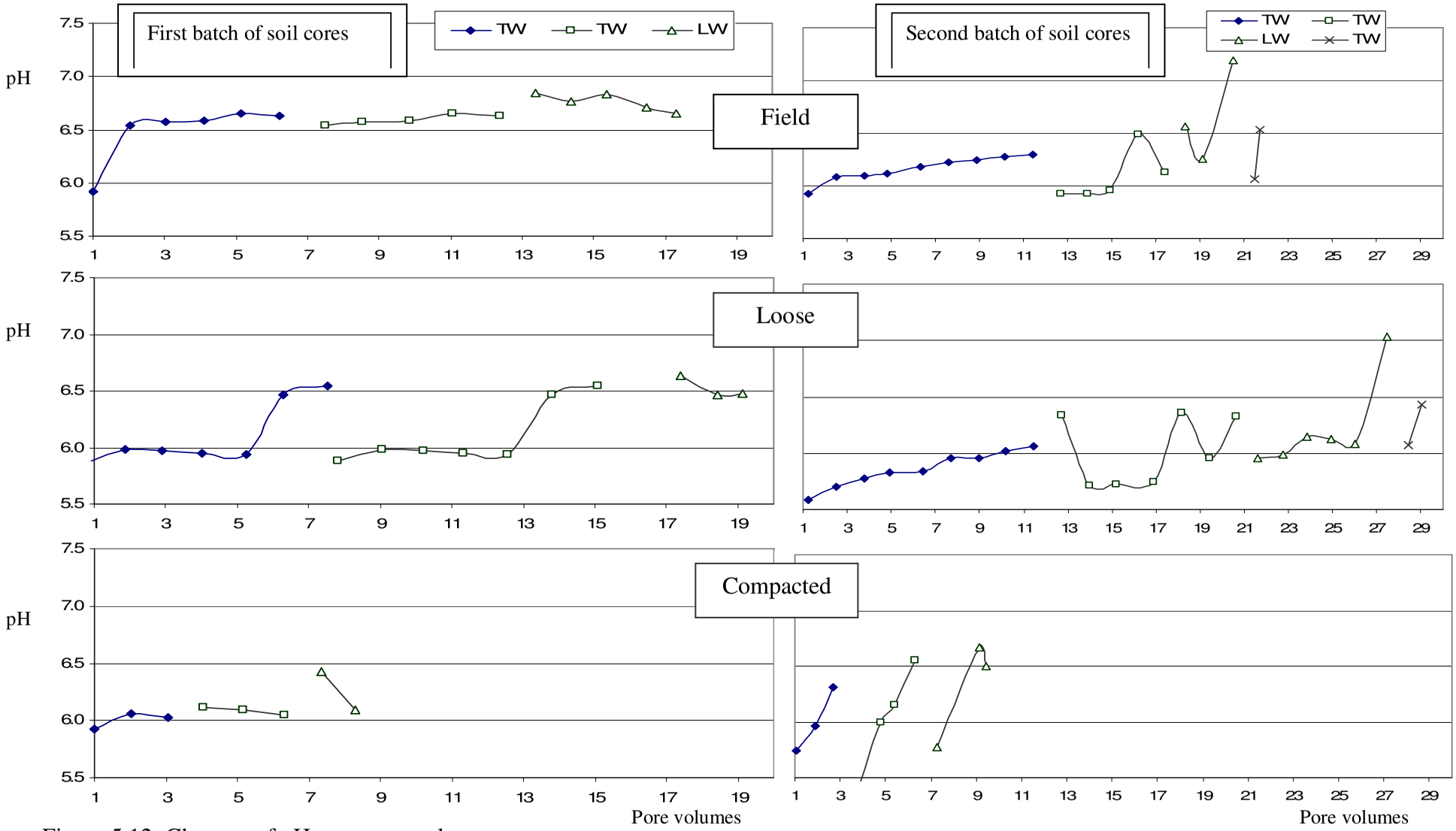


Figure 5.12: Changes of pH over pore volumes

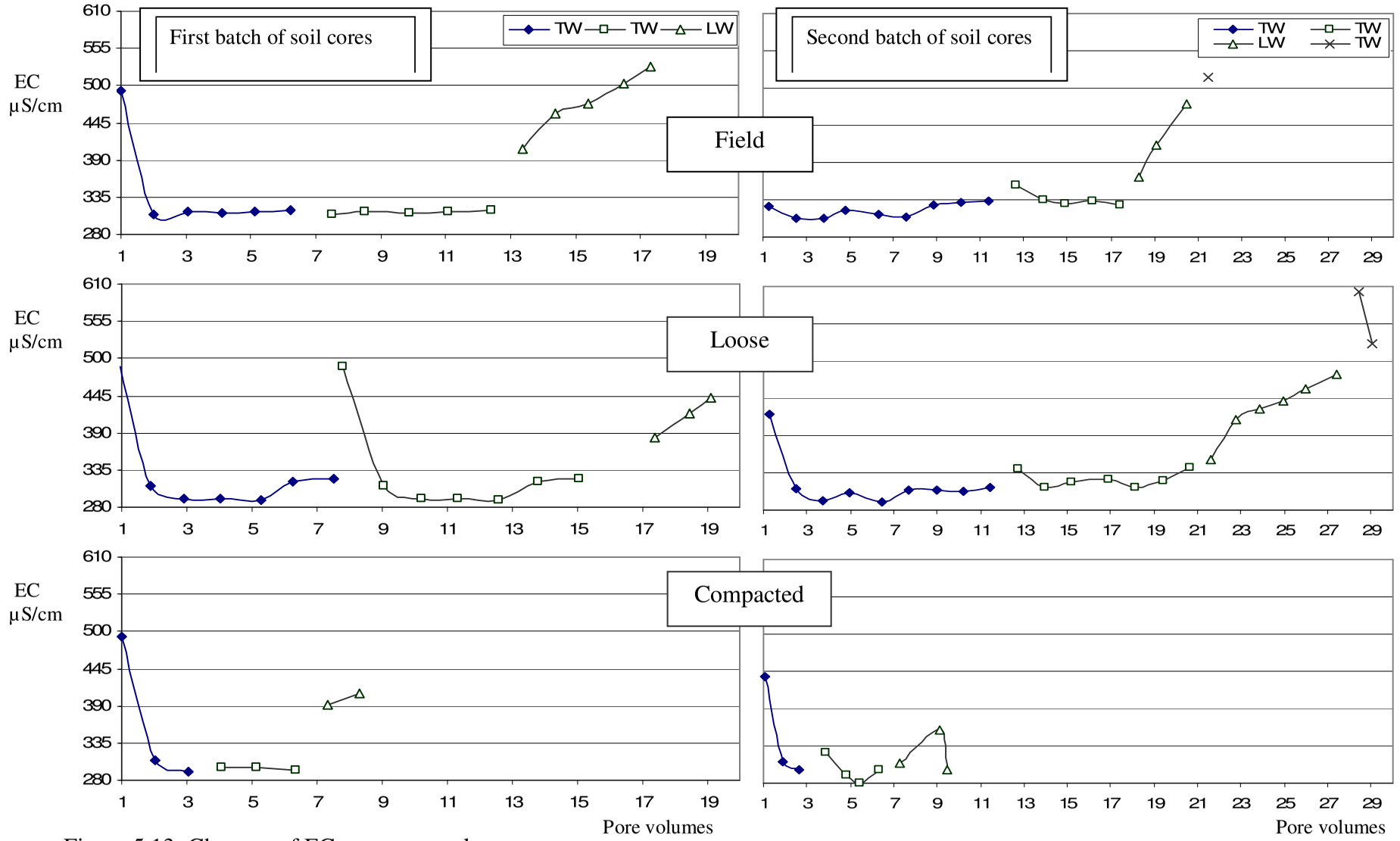


Figure 5.13: Changes of EC over pore volumes

5.4.3 Summary of Changes in pH, EC and SAR of leachate

The changes in pH, EC and SAR of the leachate with sequential application of tap water and laundry water for the experiments described in the previous experiment are summarised in Tables 5.6 and 5.7. The detailed chemical properties associated with these leachate samples are presented in Appendix I. These leachate samples were taken from the first and second batches of cores that included a sequence of four leaching treatments (TW, TW, LW and TW). The tap water leachate was randomly selected from the second tap water leaching in the sequence, while that of the laundry water leachate was randomly selected from the following leaching of laundry water (third in the sequence). From Table 5.6 it can be seen that there was little significant change in the properties of the leachate when the soil cores were irrigated with tap water. However, the leachate from laundry water (Table 5.7) experienced a significant decline in pH, EC and SAR when the soil cores were irrigated with laundry water and the leachate became similar in properties to the leachate from tap water. pH, EC and SAR of the laundry water leachate was reduced to 31%, 45% and 85% of the laundry water used for leaching. In comparison, the leachate with the use of laundry water was not significantly different in its characteristics to the tap water used for leaching.

Table 5.6: pH, EC and SAR of tap water, before and after leaching

Before leaching	**Tap water**		
	mean SE, with n = 3		
	pH	EC, µS/cm	SAR
	6.7 ± 0.01	388 ± 4.84	1.4 ± 0.00
After leaching	Tap water leachate		
Field	6.3	325	1.3
Loose	5.5	313	1.4
Compacted	6.04	295	1
mean ± SE, with (n = 3)	6.05 ± 0.12	310.5 ± 6.21	1.2 ± 0.08

Table 5.7: pH, EC and SAR of laundry water, before and after leaching

Before leaching	**Laundry water**		
	mean SE, with n = 3		
	pH	EC, µS/cm	SAR
	9.21 ± 0.03	752 ± 1.86	12.33*
After leaching	Laundry water leachate		
Field	6.2	416	1.6
Loose	6.5	437	2.4
Compacted	6.4	384	1.4
mean ± SE, with (n = 3)	6.37 ± 0.13	412 ± 12.90	1.8 ± 0.26

* Only one laundry water leachate was analysed for SAR

Combining these results with the results from the previous sections (section 5.3.2 and 5.4.2) it is suggested that when laundry water is applied to soils after the soils being saturated by rain or application of potable water, the leachate has the chemical properties that is not significantly differ from those of the tap water despite a significant decrease in the K_{sat} of the soils.

However, there was little data to justify the changes in these chemical properties when laundry water application in soils was followed by rain or the application potable water. From section 5.4.2, the fourth tap water leachate had an average pH similar to that of original tap water (n = 4), but its EC was increased by 30% (n = 3). Therefore, with a considerably high level of uncertainty, it could be said that the application of potable water or rain on the soils that are saturated by laundry water would produce leachate with the quality not significantly differ from that of the tap water leachate. The analysis of this last tap water leachate (fourth in the sequence of TW, TW, LW, and TW) was limited in number of replicates and representativeness due to the fact that the rate of discharge through the soil cores was too small. This flux was as small as 7.55×10^{-4} cm/min (0.453 mm/h) at the time of experiment. This dramatic reduction in flux and K_{sat} were discussed previously in section 5.3.2.

These results indicate that the typical red Ferrosol soil used for these experiments is capable of retaining most salts and is effective in modifying the leachate quality such that in worst case scenario when the previously wet soil is irrigated with

laundry water, the scope for ground water and surface water contamination is reduced. This is because the properties of the leachate are naturally modified through the processes of filtration, adsorption and purification. However, a substantial reduction in EC and SAR of the laundry water leachate indicates that the soil is subjected to salt accumulation. This would make the soil vulnerable to the process of contamination and subsequent degradation. According to Hillel (2004), an excessive accumulation of salts in the soil can cause a decline in soil productivity and modify soil properties such as swelling, porosity, water retention and permeability.

Chapter 6

Conclusions and Recommendations

6.1 Achievement of Objectives

With completion of this project, the following objectives were achieved:

- Background studies and literatures on the soil and water interactions were reviewed. This background information was expanded to include the properties and effects of waste water in general, but specifically laundry water to study its impact on the soil hydraulic properties.

- Experimental protocols to measure soil water characteristics, saturated hydraulic conductivity, pH and EC were examined and the feasible methods were adopted for the experiments.

- Soil water retention at near saturation (low suctions) and at field capacity were obtained by conducting experiments to measure soil water characteristics using the suction plate apparatus. However, soil water retention at wilting point could not be achieved due to unavailability of equipment during the project period.

- Undisturbed and disturbed soil cores was used to design three soil treatments referred to as field, loose and compacted soil which were used in various experiments to investigate the effects of laundry water irrigation on soil hydraulic properties. Soil water retention and saturated conductivity of these soil treatments for various sequential leaching scenarios were compared. One of the project findings was that the compacted soils had lower water content at saturation, but retained more water at higher suctions including field capacity.

- The effects laundry water applications corresponding to two soil conditions (initially unsaturated and initially saturated soils) were examined. The application of potable water or rain after laundry water irrigation resulted in a significant reduction in the value of saturated hydraulic conductivity..

- Changes in chemical and ion properties of soil and leachate investigated with measurements of pH, EC and SAR showed that the soil was capable of purifying the drainage water. However, the soil itself becomes susceptible to the process of salt accumulation and degradation.

6.2 Summary and Conclusions

This research project evaluated the effects of laundry water reuse on the hydraulic properties of a typical soil in Toowoomba (a Ferrosol) that covers over 90% of the soils found in the Toowoomba city area. The soil was slightly acidic with a CEC of 16.31 meq./100 g soil and an ESP of 0.86% which indicates little dispersive and swelling behaviour of this soil.. For undisturbed and disturbed soil conditions studied, the compacted soil treatment was found to retain the highest moisture at field capacity compared with the field and loose soil treatments which did not differ significantly among themselves with respect to water content at field capacity.

The water characteristic curves of the three soil treatments studied at low matric suctions (0-10 kPa) showed that field cores had similar water contents as the compacted cores at saturation. However, as the matric suction increased, the field and loose cores drained rapidly and were able to retain similar and smaller amount of water than the compacted soil samples at a matric suction of 10 kPa.

When laundry water was applied to the initially moist or unsaturated soil cores, the saturated hydraulic conductivity was found to be reduced by an average of 90%. The most dramatic reduction occurred for loose soil cores where the value of K_{sat} was reduced by 97%. When laundry water was applied to the initially saturated soils, the values of K_{sat} were found to be reduced by 80 ± 6%. The most reduction

occurred again for the loose soil cores (91%). Furthermore, when these samples which were saturated by laundry water were further infiltrated by tap water (to simulate the scenario where laundry water irrigation was followed by rain), a further reduction of K_{sat} occurred (61± 8%). The compacted soil cores experienced the most reduction in K_{sat} (as high as 75%) when tap water was applied after the soils were saturated by laundry water.

The characteristic of the drainage water (pH, EC and SAR) studied by leaching soil cores with tap water showed very similar chemical properties for the leachate as the tap water. In addition, the leachate of the laundry water had pH, EC and SAR similar to those of the tap water leachate. The laundry water leachate from the initially saturated soil cores (the irrigation of laundry water after the soils were saturated by tap water) was found to have 55% of the original salt concentration, and only 15% of the original SAR.

These results show that the application of laundry water caused significant decrease in the values of soil K_{sat}. Application of laundry water to unsaturated soils caused a higher reduction of K_{sat} than when laundry water was applied to saturated soils.

If the laundry water is used to irrigate lawns and garden beds, the infiltration of laundry water into the soils would be slowest in the old garden beds and lawns as these are subjected to natural settlement and some compaction. Any chance irrigation of laundry water into these soils following rain or previous irrigation with potable water would further reduce the infiltration rate of water into these soils. Furthermore, the process could be worse if the soils receive high intensity rainfall or potable water following a full irrigation with laundry water. Therefore, laundry water should be applied at low application rates over a relatively long application time. Laundry water application should be avoided when heavy rain is expected.

The quality of drainage water studied suggests that the soil was capable of retaining salts and purifying the leachate. Therefore, the drainage water would pose little risk of ground water contamination in areas where ground water is not shallow, but the soil will become more exposed to degradation from irrigation induced salinity. This

aspect of soil degradation resulting from the irrigation of laundry water requires further research.

6.3 Recommendation for Further Studies

Further investigations are highly recommended to conduct research to improve our understanding of the effects of laundry water irrigation on the soil environment. Improved understanding of the interaction between laundry water and soil properties would help to judge the suitability of reusing laundry water as well as to identify management practices and remedies to minimise its impacts on soil and water. A number of recommendations for further studies are summarised below:

- Water retention of soils needs further investigation, especially with respect to the plant available water and wilting point as laundry water is saline and alkaline. This information would provide the range of water contents that would allow plant water use with some degree of tolerance to salt and alkalinity.

- Field studies need to be conducted with adequate replication for determining the effects of laundry water on the hydraulic conductivity under realistic infiltration rates to improve the accuracy of results obtained in this study.

- Laundry water can affect chemical and physical properties. There is very little information on the physical properties (e.g. aggregate stability and dispersion and soil structure) of soil when laundry water is used over a long period of time. This aspect need further investigation.

- Other soil chemical and hydrological properties also need to be investigated to obtain a comprehensive understanding of the soil interaction with nutrients in addition to salt present in laundry water. Consideration of various hydrological properties such as climate, rainfall and ground water

characteristics would provide better understanding of the possible effects of large scale reuse of laundry water for irrigation.

- The effects of reusing laundry water on soil properties should be expanded to account for the spatial and temporal variability. The soil was able to purify the quality of drainage water during the relatively short periods of irrigation. Therefore, the soil capacity to receive laundry water irrigation without being degraded will indicate the maximum time and loading rate of laundry water application.

- Further research on plants that can tolerate and benefit from laundry water irrigation will contribute to the better management of the laundry water reuse issue.

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Appendix A:

Project Specification

University of Southern Queensland
Faculty of Engineering and Surveying

ENG 4111/2 Research Project
PROJECT SPECIFICATION

FOR: **Amphone SIVONGXAY**

TOPIC: Evaluation of the hydraulic properties of Toowoomba soils for laundry water reuse

SUPERVISOR: Dr Rabi Misra

SPONSORSHIP: Faculty of Engineering and Surveying

PROJECT AIM: This project aims to experimentally determine the retention capacity and hydraulic conductivity of typical soils from Toowoomba region to estimate potential capacity of these soils to store laundry water and to change pH/EC of drainage water.

PROGRAMME: **Issue B, 26 August 2005**

5. Research background information on storage and hydraulic properties of soils in relation to water, salt and nutrient loading

6. Devise experimental protocols to measure soil water characteristic, hydraulic conductivity, pH and Electrical Conductivity (EC) of soils and water using the clay soil from the Agricultural Field Station

7. Compare soil water characteristic and hydraulic conductivity for disturbed and undisturbed soil conditions

8. Analyse the changes in pH and EC of soil and leachate using typical laundry water for infiltration to determine the quality of drainage water

9. Undertake experiments to analyse changes in soil and water quality when laundry water application in soils is followed by rain or application of potable water for irrigation

As time permits:

10. Expand the above tests to other soils.

AGREE:

----------(Student) ----------(Supervisor)

Date ---------- ----------

Appendix B:

Field bulk density, moisture contents and plastic limit

Appendix B: Filed bulk density, moisture contents, and plastic limit

Replicates	Depth (cm)	Ring No	Tin (g)	Tin + wet soil (g)	Tin + dry soil (g)	oven dried soil (g)	W C by weight (%)	Volume (cm3)	Bulk Desity (g/cm3)	W C by volume (%)
1	2 to 5	R040	40.72	152.46	128.39	87.67	27.46	66.19	1.32	36.37
	5 to 8	R043	41.41	157.58	133.22	91.81	26.53	66.19	1.39	36.81
2	2 to 5	R042	41.20	136.04	115.56	74.36	27.54	66.19	1.12	30.94
	5 to 8	R041	41.67	126.03	108.17	66.50	26.86	66.19	1.00	26.98
3	2 to 5	R031	42.11	142.57	122.41	80.30	25.11	66.19	1.21	30.46
	5 to 8	R032	41.24	131.58	112.79	71.55	26.26	66.19	1.08	28.39
4	2 to 5	R039	41.52	147.62	126.18	84.66	25.32	66.19	1.28	32.39
	5 to 8	R307	41.25	146.02	123.31	82.06	27.67	66.19	1.24	34.31
5	2 to 5	R034	41.50	132.93	114.57	73.07	25.13	66.19	1.10	27.74
	5 to 8	R033	41.11	135.72	115.77	74.66	26.72	66.19	1.13	30.14
					Average =	78.66	26.46	66.19	1.19	31.45
					SE =	2.51	0.31		0.04	1.10

Air dried moisture content

Air dried moisture content (%)			
Tin (g)	Tin + wet soil (g)	Tin + dry soil (g)	W C by weight (%)
41.50	126.4	117.15	12.23
41.11	112.02	104.68	11.55
42.11	131.32	122.06	11.58
40.72	127.07	118.16	11.51
		Average =	11.72
		SE =	0.17

Plastic limit

Tin (g)	Tin + wet soil (g)	Tin + oven dried soil (g)	Plastic Limit (%), g/100g
41.66	57.27	54.04	26.09
41.13	52.09	49.83	25.98
41.41	50.39	48.5	26.66
41.07	51.62	49.37	27.11
38.78	49.01	46.82	27.24
		Average =	26.61
		SE =	0.26

Appendix C:

Paired T-test for field BD and WC of the soil cores from two different depths

Appendix C: Paired T-test

BD 2-5 cm	BD 5-8 cm	WCg 2-5 cm	WCg 5-8 cm	WCv 2 -5 cm	WCv 5- 8 cm
1.32	1.39	27.46	26.53	36.37	36.81
1.12	1	27.54	26.86	30.94	26.98
1.21	1.08	25.11	26.26	30.46	28.39
1.28	1.24	25.32	27.67	32.39	34.31
1.1	1.13	25.13	26.72	27.74	30.14

t-Test: Paired Two Sample for Means

	BD 2-5 cm	*BD 5-8 cm*
Mean	1.206	1.168
Variance	0.00928	0.02297
Observations	5	5
Pearson Correlation	0.834928373	
Hypothesized Mean Difference	0	
df	4	
t Stat	0.957814115	
P(T<=t) one-tail	0.196198249	
t Critical one-tail	2.131846486	
P(T<=t) two-tail	0.392396499	
t Critical two-tail	2.776450856	

t-Test: Paired Two Sample for Means

	WCg 2-5 cm	*WCg 5-8 cm*
Mean	26.112	26.808
Variance	1.61297	0.28277
Observations	5	5
Pearson Correlation	-0.1287	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.08182	
P(T<=t) one-tail	0.170098	
t Critical one-tail	2.131846	
P(T<=t) two-tail	0.340196	
t Critical two-tail	2.776451	

t-Test: Paired Two Sample for Means

	WCv 2 -5 cm	*WC v 5- 8 cm*
Mean	31.58	31.326
Variance	10.00245	16.97323
Observations	5	5
Pearson Correlation	0.754225099	
Hypothesized Mean Difference	0	
df	4	
t Stat	0.209910474	
P(T<=t) one-tail	0.421997903	
t Critical one-tail	2.131846486	
P(T<=t) two-tail	0.843995806	
T Critical two-tail	2.776450856	

Appendix D:

Calculation of moist soil needed for disturbed cores

Appendix D: Moist Soil Calculation

* Air dried moisture content = 11.72 ± 0.17 %, PL = 26.61± 0.26 %

The amount of wet soil needed for preparation of compacted cores was derived as follows.

(1) When the air-dry moisture content ($M\%$) was known, the correction from air-dry to oven-dry was: oven-dry result = $\frac{Air\_dry\_result \times (100)}{(100 + M)}$.

(2) The air-dry soil had a gravimetric moisture content of 11.72%. Therefore, (100+11.72) g of air-dry soil was equivalent to 100 g of oven-dry soil.

(3) Predetermined moisture content was 1.2PL or 1.2×26.61% = 32 %. Therefore, to produce 100 g of oven dried soil with a moisture content of 32 %, the amount of water needed was: 132 – 111.72 = 20.28 g.

(4) The oven soil of 100 g was equivalent to 132 g of moist soil. Thus, the factor of 132/100 or 1.32 would be used to calculate the equivalent moist soil for a specified oven dried soil.

(5) From $BD = M_s / V_B$, $M_s = BD \times V_B$

Therefore, loose core (3 cm high) would need M_s of 1.05×66.19 = 69.5 g. This oven dried soil was equivalent of 69.5×1.32 = 91.7 g of moist soil. Similarly, compacted core (3 cm high) would need M_s of 1.20×66.19 = 79.43 g. This oven dried soil was equivalent of 79.43×1.32 = 104.8g of moist soil.

(6) The loose core with 6 cm in height would need 91.7×2 = 183.4 g of moist soil while the compacted one would need 209.6 g of moist soil.

Appendix E:

Data for the Calculation of Soil Water Contents at Different Matric Suctions

Appendix E: Data for the Calculation of Soil Water Contents at Different Matric Suctions

Correction factor (tape, cloth and 1 cm ring)

Ring No and weight (g)		1 cm ring (g)	cloth (g)	rubber band (g)	tapes (g)	trim out (g)	(g) extra weight	ov dried (g)	Pore V %
R030	68.5	22.7	1.15	1.30	5	0.7	97.95	79.6	54.62
R032	68.5	22.3	1.15	0.60	5	1.2	96.35	76.1	56.61
R039	68.5	23.1	1.15	1.20	5	0.9	98.05	84.6	51.77
R041	71.2	24.8	1.15	1.20	5	0.7	102.65	69.5	60.38
R044	71.2	24.8	1.15	1.30	5	0.8	102.65	69.6	60.26
R040	71.2	24.7	1.15	1.10	5	0.7	102.45	69.7	60.32
R037	67.7	22.2	1.15	0.90	5	0.9	96.05	79.7	54.56
R033	67	22.3	1.15	1.30	5	0.8	95.95	79.6	54.62
R036	68.4	23.2	1.15	1.30	5	0.7	98.35	79.9	54.45

Cores' weight (g) at varying suction

Core No	**0 cm**	**-10 cm**	**-30 cm**	**-50 cm**	**-70 cm**	**-100 cm**	**- 3.3 m**	**-70 cm**	**-50 cm**	**-30 cm**	**-10 cm**	**-0 cm**
R030	212.6	207.7	204.5	202.9	202.1	201.5	199.5	200.8	200.9	202.5	204.5	211.9
R032	209.5	207	203.7	201.5	200.5	199.3	197.3	200.4	201.2	201.7	203.5	208.9
R039	216.8	212.8	209.7	208	207.6	206.9	207.5	207.36	207.5	208.1	208.8	216.2
R041	211.9	211	200.7	198.4	196.4	195.4	194.2	194.8	195.3	195.8	199.3	211.9
R044	211.8	209.8	201.3	197.4	196.6	195.6	194.9	195.1	194.8	195.1	197.9	211.6
R040	210.7	209.5	203.2	200.3	199.4	198	196.5	196.8	196.9	198.2	202.1	210.8
R037	211.5	211.2	208.7	206.2	203.4	204.1	202.7	203.2	203.7	204.3	207.6	211.5
R033	211.8	211.1	209	208.2	207.5	206.9	205.5	205.9	206.1	206.3	209.1	211.7
R036	213.6	213.1	211.2	210.3	209.7	208.7	205.6	207	207.1	207.60	209	213.1

(Cores' weight – extra weight = wet soil)

wet soil (g)	0 cm	-10 cm	-30 cm	-50 cm	-70 cm	-100 cm	- 3.3 m	-70 cm	-50 cm	-30 cm	-10 cm	-0 cm
R030	114.7	109.75	106.55	104.95	104.15	103.55	101.55	102.85	102.95	104.55	106.55	113.95
R032	113.2	110.65	107.35	105.15	104.15	102.95	100.95	104.05	104.85	105.35	107.15	112.55
R039	118.8	114.75	111.65	109.95	109.55	108.85	109.45	109.31	109.45	110.05	110.75	118.15
R041	109.3	108.35	98.05	95.75	93.75	92.75	91.55	92.15	92.65	93.15	96.65	109.25
R044	109.2	107.15	98.65	94.75	93.95	92.95	92.25	92.45	92.15	92.45	95.25	108.95
R040	108.3	107.05	100.75	97.85	96.95	95.55	94.05	94.35	94.45	95.75	99.65	108.35
R037	115.5	115.15	112.65	110.15	107.35	108.05	106.65	107.15	107.65	108.25	111.55	115.45
R033	115.9	115.15	113.05	112.25	111.55	110.95	109.55	109.95	110.15	110.35	113.15	115.75
R036	115.3	114.75	112.85	111.95	111.35	110.35	107.25	108.65	108.75	109.25	110.65	114.75

water content by weight (mass of water / mass of oven dried soil) = (wet soil - oven dried soil) in g / oven dried soil in g

Core No	oven dried soil (g)	0 cm	-10 cm	-30 cm	-50 cm	-70 cm	-100 cm	- 3.3 m	-70 cm	-50 cm	-30 cm	-10 cm	-0 cm
R030	79.6	0.440	0.379	0.339	0.318	0.308	0.301	0.276	0.292	0.293	0.313	0.339	0.432
R032	76.1	0.487	0.454	0.411	0.382	0.369	0.353	0.327	0.367	0.378	0.384	0.408	0.479
R039	84.6	0.404	0.356	0.320	0.300	0.295	0.287	0.294	0.292	0.294	0.301	0.309	0.397
R041	69.5	0.572	0.559	0.411	0.378	0.349	0.335	0.317	0.326	0.333	0.340	0.391	0.572
R044	69.6	0.568	0.540	0.417	0.361	0.350	0.335	0.325	0.328	0.324	0.328	0.369	0.565
R040	69.7	0.553	0.536	0.445	0.404	0.391	0.371	0.349	0.354	0.355	0.374	0.430	0.555
R037	79.7	0.449	0.445	0.413	0.382	0.347	0.356	0.338	0.344	0.351	0.358	0.400	0.449
R033	79.6	0.455	0.447	0.420	0.410	0.401	0.394	0.376	0.381	0.384	0.386	0.421	0.454
R036	79.9	0.442	0.436	0.412	0.401	0.394	0.381	0.342	0.360	0.361	0.367	0.385	0.436

Volumetric moisture contents at different suctions

Core No	ov dried soil (g)	Bulk Density	0 cm	-10 cm	-30 cm	-50 cm	-70 cm	-100 cm	- 3.3 m	-70 cm	-50 cm	-30 cm	-10 cm	-0 cm
Field														
R030	79.6	1.203	0.530	0.456	0.407	0.383	0.371	0.362	0.332	0.351	0.353	0.377	0.407	0.519
R032	76.1	1.150	0.560	0.522	0.472	0.439	0.424	0.406	0.375	0.422	0.434	0.442	0.469	0.551
R039	84.6	1.278	0.516	0.456	0.409	0.383	0.377	0.366	0.375	0.373	0.375	0.384	0.395	0.507
Mean =	80.100	1.210	0.535	0.478	0.429	0.402	0.391	0.378	0.361	0.382	0.388	0.401	0.424	0.526
STDEV =	4.272	0.065	0.022	0.038	0.037	0.032	0.029	0.024	0.025	0.036	0.042	0.036	0.040	0.023
SE =	2.466	0.037	0.013	0.022	0.021	0.019	0.017	0.014	0.015	0.021	0.024	0.021	0.023	0.013
Loose														
R041	69.5	1.050	0.601	0.587	0.431	0.397	0.366	0.351	0.333	0.342	0.350	0.357	0.410	0.601
R044	69.6	1.053	0.598	0.568	0.440	0.381	0.368	0.353	0.343	0.346	0.341	0.346	0.388	0.595
R040	69.7	1.052	0.582	0.564	0.469	0.425	0.411	0.390	0.368	0.372	0.374	0.393	0.452	0.583
Mean =	69.600	1.052	0.594	0.573	0.446	0.401	0.382	0.365	0.348	0.353	0.355	0.365	0.417	0.593
STDEV =	0.100	0.002	0.010	0.012	0.020	0.022	0.025	0.022	0.018	0.016	0.017	0.025	0.032	0.009
SE =	0.058	0.001	0.006	0.007	0.011	0.013	0.015	0.013	0.010	0.009	0.010	0.014	0.019	0.005
Compacted														
R037	79.7	1.204	0.540	0.536	0.498	0.460	0.418	0.428	0.407	0.415	0.422	0.431	0.481	0.540
R033	79.6	1.203	0.548	0.537	0.505	0.493	0.483	0.474	0.452	0.459	0.462	0.465	0.507	0.546
R036	79.9	1.207	0.534	0.527	0.498	0.484	0.475	0.460	0.413	0.434	0.436	0.443	0.465	0.527
Mean =	79.733	1.205	0.541	0.533	0.500	0.479	0.459	0.454	0.424	0.436	0.440	0.446	0.484	0.538
STDEV =	0.153	0.002	0.007	0.006	0.004	0.017	0.036	0.023	0.025	0.022	0.020	0.017	0.021	0.010
SE =	0.088	0.001	0.004	0.003	0.003	0.010	0.021	0.013	0.014	0.013	0.012	0.010	0.012	0.006

Appendix F:

Flux, K_{sat}, pH and EC of the leachate from four batches of soil cores

Appendix F1: Flux,K_{sat}, pH and EC of the leachate from the first batch of soil cores.

Appendix F2: Flux, K_{sat}, pH and EC of leachate from the second batch of soil cores.

Appendix F3: Flux, K_{sat}, pH and EC of the leachate from the third batch of soil cores.

Appendix F4: Flux, K_{sat}, pH and EC of the leachate from the fourth batch of soil cores.

Appendix F1: Flux, K_{sat}, pH and EC of the leachate from the first batch of soil cores

Table F1.A: First batch samples, first leaching by tap water

First leaching: tap water						
Treatment:	Compacted	Field	Loose	Compacted	Field	Loose
Ring no.	Discharge Q (cm^3)			Flux = Q/AT (cm/min)		
Time (min)	R052	R055	R057	R052	R055	R057
5	12	119	72	0.109	1.079	0.653
10	8	105	71	0.073	0.952	0.644
15	10	27	66	0.091	0.245	0.598
20	9	99	50	0.082	0.897	0.453
25	8	77	59	0.073	0.698	0.535
30	9	47	58	0.082	0.426	0.526
35	9	29	59	0.082	0.263	0.535
40	9	24	57	0.082	0.218	0.517
45	10	48	58	0.091	0.435	0.526
50	9	71	60	0.082	0.644	0.544
55	8	45	54	0.073	0.408	0.490
60	8	60	59	0.073	0.544	0.535
65	8	57	55	0.073	0.517	0.499
70	8	62	50	0.073	0.562	0.453
75	9	47		0.082	0.426	
80	8	46		0.073	0.417	
85	7	55		0.063	0.499	
90	7	25		0.063	0.227	
95	7			0.063		
Average of last 4 readings of flux (cm/min) :				0.066	0.392	0.494
	Calculate h / l = 7/6					
Ksat (cm/min) = Av flux *l / h = Av flux* 6/7 =				0.056	0.336	0.423
	Ksat (mm/h) =			33.8	201.6	254.09

Table F1.B: First batch samples, second leaching with tap water

Second leaching: tap water						
Time (min)	Compacted	Field	Loose	Flux = Q/AT (cm/min)		
5	12	36	82	0.109	0.326	0.743
10	14	32	68	0.127	0.290	0.616
15	14	35	64	0.127	0.317	0.580
20	12	31	65	0.109	0.281	0.589
25	11.5	29	68	0.104	0.263	0.616
30	13	32	72	0.118	0.290	0.653
35	10	29	71	0.091	0.263	0.644
40	10	29	63	0.091	0.263	0.571
45	10	30	59	0.091	0.272	0.535
50	10	22	60	0.091	0.199	0.544
55	11	25	61	0.100	0.227	0.553
60	10	26	58	0.091	0.236	0.526
65	10.5	26	53	0.095	0.236	0.480
70	12	24	54	0.109	0.218	0.490
75	11	24	52	0.100	0.218	0.471
80	10	18	64	0.091	0.163	0.580
85	10	24	59	0.091	0.218	0.535
90	10	22	55	0.091	0.199	0.499
95	10	24	55	0.091	0.218	0.499
100	10	24	56	0.091	0.218	0.508
105	10	25	55	0.091	0.227	0.499
110		24			0.218	
Average of last 4 readings of flux (cm/min) :				0.091	0.220	0.501
	Calculate h / l = 7/6					
Ksat (cm/min) = Av flux *l / h = Av flux* 6/7 =				0.078	0.188	0.429
	Ksat (mm/h) =			46.62	113.06	257.59

Table F1.C: First batch samples, third leaching with laundry water

Third leaching: laundry water						
Time (min)	Compacted	Field	Loose	Flux = Q/AT (cm/min)		
5	11	34	47	0.100	0.308	0.426
10	8.5	21	34	0.077	0.190	0.308
15	8	18	27	0.073	0.163	0.245
20	6.5	18	20	0.059	0.163	0.181
25	7	15	16	0.063	0.136	0.145
30	7	15	11	0.063	0.136	0.100
35	7	14	10	0.063	0.127	0.091
40	6	13	9	0.054	0.118	0.082
45	5	16	6	0.045	0.145	0.054
50	6	15	5	0.054	0.136	0.045
55	7	15	4	0.063	0.136	0.036
60	5	14	3	0.045	0.127	0.027
65	5	14	3	0.045	0.127	0.027
70	5	16	2	0.045	0.145	0.018
75	5	14	2	0.045	0.127	0.018
80	4	13	2	0.036	0.118	0.018
85	4	13	2	0.036	0.118	0.018
90	4	13	2	0.036	0.118	0.018
95	3	12	1	0.027	0.109	0.009
100	3	14	1	0.027	0.127	0.009
105	4	12	1	0.036	0.109	0.009
110	3	12	1.5	0.027	0.109	0.014
115	3	17	1	0.027	0.154	0.009
120	3	12	1	0.027	0.109	0.009
125	3		1	0.027		0.009
Average of last 4 readings of flux (cm/min) :				0.027	0.120	0.010
	Calculate h / l = 7/6					
Ksat (cm/min) = Av flux *l / h = Av flux* 6/7 =				0.023	0.103	0.009
	Ksat (mm/h) =			13.99	61.77	5.25

Table F1.D: First batch samples, forth leaching with tap water

Fourth leaching: tap water						
Time (min)	Compacted	Field	Loose	Flux = Q/AT (cm/min)		
5	2.5	3	8	0.023	0.027	0.073
10	2.5	1	4	0.023	0.009	0.036
15	1.5	2	4	0.014	0.018	0.036
20	1	1	4	0.009	0.009	0.036
25	0.75	1	3	0.007	0.009	0.027
30	0.75	0.66	3	0.007	0.006	0.027
35	1	0.66	2.5	0.009	0.006	0.023
40	1	0.66	2.5	0.009	0.006	0.023
45	1	0.66	2.5	0.009	0.006	0.023
50	1	0.66	2.5	0.009	0.006	0.023
55	1	0.66	2.5	0.009	0.006	0.023
60	1		2.5	0.009		0.023
65						
Average of last 4 readings of flux (cm/min) :				0.009	0.006	0.023
	Calculate h / l = 7/6					
Ksat (cm/min) = Av flux *l / h = Av flux* 6/7 =				0.008	0.005	0.019
	Ksat (mm/h) =			4.66	3.08	11.66

Table F1.E: Summary of results

	Saturated Hydraulic Conductivity (mm/h)		
Treatment	Compacted	Field	Loose
TW	33.8	201.64	254.09
TW	46.6	113.06	257.59
LW	13.99	61.77	5.25
TW	4.67	3.08	11.66

Table F1.F: Changes in pH and EC of the leachate (First batch samples)

Sample: R052 (compacted)				
Leachate:	ml	Pore volume	pH	EC, (10^{-3} ds/m)
First leaching with tap water				
1A	74	1.01	5.92	492
1B	75	2.04	6.06	310
1C	75	3.07	6.02	293
Second leaching with tap water				
1A	72.5	4.06	6.11	310
1B	80	5.16	6.09	298
1C	86	6.34	6.05	295
Third leaching with laundry water				
1A	73	7.34	6.43	392
1B	71	8.31	6.09	408

Sample: R055 (Field)				
Leachate:	ml	Pore volume	pH	EC, (10^{-3} ds/m)
First leaching with tap water				
2A	75	1.01	5.92	492
2B	75	2.03	6.54	309
2C	75	3.04	6.57	314
2D	80	4.12	6.58	312
2E	75	5.14	6.65	313
2F	81	6.23	6.63	316
Second leaching with tap water				
2A	94	7.50	6.54	309
2B	75	8.51	6.57	314
2C	100	9.86	6.58	312
2D	89	11.07	6.65	313
2E	97	12.38	6.63	316
Third leaching with laundry water				
2A	73	13.36	6.84	406
2B	75	14.38	6.76	458
2C	74	15.38	6.83	474
2D	81	16.47	6.71	503
2E	61	17.30	6.65	528

Sample: R057 (Loose)				
Leachate:	ml	Pore volume	pH	EC, (10^{-3} ds/m)
First leaching with tap water				
3A	75	0.94	5.88	489
3B	75	1.88	5.98	312
3C	83	2.91	5.97	293
3D	88	4.01	5.95	292
3E	100	5.26	5.94	291
3F	81	6.28	6.47	318
3G	100	7.53	6.55	323
Second leaching with tap water				
3A	23	7.81	5.88	489
3B	100	9.06	5.98	312
3C	91	10.20	5.97	293
3D	90	11.33	5.95	292
3E	100	12.58	5.94	291
3F	100	13.83	6.47	318
3G	100	15.08	6.55	323
3H	105	16.39	-	-
Third leaching with laundry water				
3A	81	17.40	6.64	382
3B	84	18.45	6.47	418
3C	53	19.11	6.48	441

Appendix F2: Flux, K_{sat}, pH and EC of the leachate for the second batch of soil cores.

Table F2.A: Second batch samples, first tap water leaching

Treatment:	Compacted	Field	Loose	Compacted	Field	Loose
Ring no.	Discharge Q (cm^3)			Flux = Q/AT (cm/min)		
Time (min)	R056	R054	R053	R056	R054	R053
5	10	142	143	0.091	1.287	1.296
10	8	130	120	0.073	1.179	1.088
15	7	119	132	0.063	1.079	1.197
20	7	119	128	0.063	1.079	1.160
25	6	120	118	0.054	1.088	1.070
30	8	108	105	0.073	0.979	0.952
35	7	102	113	0.063	0.925	1.024
40	6	98	118	0.054	0.888	1.070
45	6	97	111	0.054	0.879	1.006
50	6	100	100	0.054	0.907	0.907
55	7	105	106	0.063	0.952	0.961
60	6	95	102	0.054	0.861	0.925
65	6	84	108	0.054	0.761	0.979
70	6	90	99	0.054	0.816	0.897
75	6	87	99	0.054	0.789	0.897
80	5	88	88	0.045	0.798	0.798
85	6	89	96	0.054	0.807	0.870
90	6	89	100	0.054	0.807	0.907
95		85	95		0.771	0.861
100		90	100		0.816	0.907
105		90	100		0.816	0.907
110		79	75		0.716	0.680
115		80	89		0.725	0.807
120		79	89		0.716	0.807
125		78	72		0.707	0.653
130		78	84		0.707	0.761
135		78	84		0.707	0.761
140		78	84		0.707	0.761
145			84			0.761
Average of last 4 readings of flux (cm/min) :				0.052	0.707	0.761
	Calculate h / l = 7/6					
Ksat (cm/min) = Av flux *l / h = Av flux* 6/7 =				0.045	0.606	0.653
	Ksat (mm/h) =			26.81	363.65	391.63

Table F2.B: Second batch samples, second tap water leaching

Second leaching: tap water						
Treatment:	Compacted	Field	Loose	Compacted	Field	Loose
Time (min)	R056	R054	R053	Flux = Q/AT (cm/min)		
5	11	58	121	0.100	0.526	1.097
10	10	56	128	0.091	0.508	1.160
15	8	55	127	0.073	0.499	1.151
20	10	56	127	0.091	0.508	1.151
25	10	46	132	0.091	0.417	1.197
30	10	52	132	0.091	0.471	1.197
35	9	52	128	0.082	0.471	1.160
40	9	51	128	0.082	0.462	1.160
45	10	50	130	0.091	0.453	1.179
50	11	51	136	0.100	0.462	1.233
55	10	50	128	0.091	0.453	1.160
60	8	50	129	0.073	0.453	1.169
65	10	49	129	0.091	0.444	1.169
70	10	48	129	0.091	0.435	1.169
75	10	48	128	0.091	0.435	1.160
80	10	50		0.091	0.453	
85	10	50		0.091	0.453	
90	10	50		0.091	0.453	
95						
Average of last 4 readings of flux (cm/min) :				0.091	0.449	1.167
	Calculate h / l = 7/6					
Ksat (cm/min) = Av flux *l / h = Av flux* 6/7 =				0.078	0.385	1.00
	Ksat (mm/h) =			46.62	230.78	600.26

Table F2.C: Second batch samples, third laundry water leaching

Third leaching, laundry water						
Treatment:	Compacted	Field	Loose	Compacted	Field	Loose
Time (min)	R056	R054	R053	Flux = Q/AT (cm/min)		
5	14	42	76	0.127	0.381	0.689
10	9	26	41	0.082	0.236	0.372
15	8	14	26	0.073	0.127	0.236
20	6	9	26	0.054	0.082	0.236
25	6	7	32	0.054	0.063	0.290
30	6	6	28	0.054	0.054	0.254
35	5	6	26	0.045	0.054	0.236
40	5	4	26	0.045	0.036	0.236
45	5	4	22	0.045	0.036	0.199
50	4	2	20	0.036	0.018	0.181
55	4	3	18	0.036	0.027	0.163
60	5	2	20	0.045	0.018	0.181
65	5	2	17	0.045	0.018	0.154
70	4	3	17	0.036	0.027	0.154
75	3	2	16	0.027	0.018	0.145

80	3	2	16	0.027	0.018	0.145
85	3	2	16	0.027	0.018	0.145
90	3	2	16	0.027	0.018	0.145
95	3			0.027		
Average of last 4 readings of flux (cm/min) :				0.027	0.018	0.145
	Calculate h / l = 7/6					
Ksat (cm/min) = Av flux *l / h = Av flux* 6/7 =				0.023	0.016	0.124
	Ksat (mm/h) =			13.99	9.32	74.6

Table F2.D: Second batch samples, forth tap water leaching

Fourth leaching, tap water						
Treatment:	Compacted	Field	Loose	Compacted	Field	Loose
Time (min)	R056	R054	R053	Flux = Q/AT (cm/min)		
5	1	8	10	0.009	0.073	0.091
10	1	6	6	0.009	0.054	0.054
15	0.5	5	6	0.005	0.045	0.054
20	0.5	5	6	0.005	0.045	0.054
25	0.5	5	7	0.005	0.045	0.063
30	0.5	4	5	0.005	0.036	0.045
35	0.5	5	7	0.005	0.045	0.063
40	0.5	5	6	0.005	0.045	0.054
45	0.75	4	7	0.007	0.036	0.063
50	0.75	5	7	0.007	0.045	0.063
55	0.75	5	6	0.007	0.045	0.054
60	0.75	5	7	0.007	0.045	0.063
65	0.5	4	9	0.005	0.036	0.082
70	0.5	4	6	0.005	0.036	0.054
75	0.5	5	7	0.005	0.045	0.063
80	0.5	6	7	0.005	0.054	0.063
85		5	7		0.045	0.063
90		5	6		0.045	0.054
95		5	7		0.045	0.063
100						
Average of last 4 readings of flux (cm/min) :				0.005	0.048	0.061
	Calculate h / l = 7/6					
Ksat (cm/min) = Av flux *l / h = Av flux* 6/7 =				0.004	0.041	0.052
	Ksat (mm/h) =			2.331	24.48	31.47

Table F2.E: Summary of results

	Saturated Hydraulic Conductivity (mm/h)		
Treatment	Compacted	Field	Loose
TW	26.81	363.65	391.63
TW	46.62	230.78	600.26
LW	13.99	9.324	74.60
TW	2.33	24.48	31.47

Table F2.F: Changes in pH and EC of the leachate (second batch samples)

Sample: R056 (compacted)				
Leachate:	ml	Pore volume	pH	EC, (10^{-3} ds/m)
First leaching with tap water				
Leachate:	ml	Pore volume	pH	EC,
1A	78	1.07	5.74	438
1B	62	1.92	5.96	311
1C	55	2.67	6.31	299
Second leaching with tap water				
1A	87	3.86	5.43	325
1B	69	4.81	5.99	291
1C	45	5.42	6.15	280
1D	64	6.30	6.55	299
Third leaching laundry water				
1A	72	7.29	5.77	310
1B	134	9.12	6.67	359
1C	24	9.45	6.5	299

Sample: R054 (Field)				
Leachate:	ml	Pore volume	pH	EC, (10^{-3} ds/m)
First leaching with tap water				
Leachate:	ml	Pore volume	pH	EC,
2A	100	1.27	5.93	325
2B	100	2.53	6.09	307
2C	100	3.80	6.1	307
2D	81	4.82	6.12	319
2E	119	6.33	6.18	314
2F	100	7.59	6.22	309
2G	100	8.86	6.25	327
2H	100	10.13	6.28	332
2I	100	11.39	6.3	334
Second leaching with tap water				
2A	100	12.66	5.93	357
2B	100	13.92	5.93	335
2C	77.5	14.91	5.96	330
2D	100	16.17	6.49	334
2E	100	17.44	6.13	327
Third leaching laundry water				
2A	68	18.30	6.56	368
2B	63	19.09	6.26	415
2C	112	20.51	7.19	477
Fourth leaching with tap water				
2A	75	21.46	6.06	515
2B	20	21.72	6.53	

Sample: R053 (Loose)				
Leachate:	ml	Pore volume	pH	EC, (10^{-3} ds/m)
First leaching with tap water				
Leachate:	ml	Pore volume	pH	EC,
3A	100	1.25	5.58	422
3B	100	2.50	5.7	312
3C	100	3.75	5.77	293
3D	94	4.93	5.83	305
3E	120	6.43	5.84	291
3F	103	7.71	5.95	310
3G	100	8.96	5.96	309
3H	100	10.21	6.02	308
3I	100	11.46	6.06	314
Second leaching with tap water				
3A	100	12.71	6.34	340
3B	100	13.96	5.71	313
3C	100	15.21	5.72	322
3D	134	16.89	5.74	325
3E	100	18.14	6.36	314
3F	101	19.40	5.95	324
3G	100	20.65	6.33	342
Third leaching laundry water				
3A	76	21.60	5.95	354
3B	94	22.78	5.99	414
3C	86	23.85	6.15	430
3D	86	24.93	6.12	441
3E	86	26.00	6.08	459
3F	115	27.44	7.03	481
fourth leaching with tap water				
3A	80	28.44	6.07	603
3B	50	29.06	6.43	525

Appendix F3: Flux, K_{sat}, leachate pH and EC of the third batch of soil cores.

Table F3.A: Third batch samples (tap water leaching only)

Tap water only						
Treatment:	Compacted	Field	Loose	Compacted	Field	Loose
Ring no.	Discharge Q (cm^3)			Flux = Q/AT (cm/min)		
	R059	R051	R050	R059	R051	R050
5	23	122	151	0.209	1.106	1.369
10	23	78	118	0.209	0.707	1.070
15	21	69	131	0.190	0.626	1.188
20	21	56	125	0.190	0.508	1.133
25	23	52	125	0.209	0.471	1.133
30	20	48	90	0.181	0.435	0.816
35	20	43	100	0.181	0.390	0.907
40	20	41	130	0.181	0.372	1.179
45	21	41	131	0.190	0.372	1.188
50	21	37	135	0.190	0.335	1.224
55	20	37	124	0.181	0.335	1.124
60	20	34	124	0.181	0.308	1.124
65	19	33	125	0.172	0.299	1.133
70	20	33	124	0.181	0.299	1.124
75	20	33	124	0.181	0.299	1.124
80	20			0.181		
Average of last 4 readings of flux (cm/min) :				0.179	0.301	1.126
	Calculate h / l = 7/6					
Ksat (cm/min) = Av flux *l / h = Av flux* 6/7 =				0.153	0.258	0.965
	Ksat (mm/h) =			92.08	155.02	579.28

Table F3.B: Changes in pH and EC of the leachate

Sample: R059 (Compacted)				
Leachate:	ml	Pore volume	pH	EC, (10^{-3} ds/m)
1A	87	1.21	5.41	393
1B	83	2.36	5.4	363
1C	101	3.76	5.39	
Sample: R051 (Field)				
2A	100	1.43	6.47	410
2B	100	2.86	6.6	391
2C	100	4.29	6.52	391
2D	100	5.71	6.63	392
2E	104	7.20	6.28	392
2F	79	8.33	6.27	396
Sample: R050 (Loose)				
3A	100	1.25	5.48	450
3B	100	2.50	5.66	386
3C	100	3.75	5.54	389
3D	100	5.00	5.61	361
3E	100	6.25	5.62	362
3F	100	7.50	5.64	360

Appendix F4: Flux, K_{sat}, leachate pH and EC of the fourth batch of soil cores.

Table F4.A: Fourth batch samples (laundry water leaching only)

Laundry water only						
Treatment:	Compacted	Field	Loose	Compacted	Field	Loose
Ring no.	Discharge Q (cm^3)			Flux = Q/AT (cm/min)		
	R057	R056	R055	R057	R056	R055
5	27	31	37	0.245	0.281	0.335
10	14	18	27	0.127	0.163	0.245
15	12	15	23	0.109	0.136	0.209
20	9	13	22	0.082	0.118	0.199
25	7	15	17	0.063	0.136	0.154
30	7	13	15	0.063	0.118	0.136
35	8	10	14	0.073	0.091	0.127
40	6	9	13	0.054	0.082	0.118
45	4	10	14	0.036	0.091	0.127
50	5	9	11.5	0.045	0.082	0.104
55	4	8	12	0.036	0.073	0.109
60	3	8	12.5	0.027	0.073	0.113
65	3	10	8	0.027	0.091	0.073
70	3	7	6	0.027	0.063	0.054
75	2	7	5	0.018	0.063	0.045
80	2.5	7	5	0.023	0.063	0.045
85	3.25	7	3	0.029	0.063	0.027
90	3.25	6	2	0.029	0.054	0.018
95	2	6	3	0.018	0.054	0.027
100	2	7	4.5	0.018	0.063	0.041
105	2	6	5	0.018	0.054	0.045
110	1.5	6	3.5	0.014	0.054	0.032
115	1.5	6	3	0.014	0.054	0.027
120			3			0.027
Average of last 4 readings of flux (cm/min) :				0.016	0.057	0.036
Calculate h / l = 7/6						
Ksat (cm/min) = Av flux *l / h = Av flux* 6/7 =				0.014	0.049	0.031
	Ksat (mm/h) =			8.16	29.14	18.65

Table F4.B: Changes in pH and EC (laundry water only)

Sample: R057 (Compacted)				
Leachate:	ml	Pore volume	pH	EC, (10-3 ds/m)
1A	76	1.00	9.15	909
1B	55	1.72	8.92	897
Sample: R056 (Field)				
2A	77	1.13	8.65	668
2B	82	2.34	7.11	645
2C	79	3.50	6.23	613
Sample: R055 (Loose)				
3A	87	1.09	5.63	759
3B	81	2.10	5.62	649
3C	90	3.23	5.75	664

Appendix G:

Bulk density and pore volume of all soil cores used in the experiment

Appendix G: Bulk densities and pore volumes of all soil cores

3 cm cores (water retention)

Ring No	Tin No	Tin weight (g)	tin+ wet soil (g)	tine+ dried soil (g)	dried soil g	WC_g	BD g/cm3	pore volume %	pore volume (ml)
Field									
R030	M29	41.5	144.1	121.1	79.6	29	1.203	54.62	36
R032	M21	41.5	142.8	117.6	76.1	33	1.150	56.61	37
R039	M45	41.1	150.9	125.7	84.6	30	1.278	51.77	34
Loose									
R041	M37	41.6	134.9	111.1	69.5	34	1.050	60.38	40
R040	M19	41.6	135	111.2	69.6	34	1.052	60.32	40
R044	M13	41.2	135.5	110.9	69.7	35	1.053	60.26	40
Compacted									
R037	M47	42.3	149.3	122	79.7	34	1.204	54.56	36
R033	M41	41.2	151.4	120.8	79.6	38	1.203	54.62	36
R036	M73	39.7	147.6	119.6	79.9	35	1.207	54.45	36

6 cm cores

1st batch	tin No	Tin (g)	tin + wet	tin+dry	dried soil	WC	BD g/cm3	Pore volume (%)	Pore Volume (ml)
R055	M41	41.2	-	127.3	86.1	-			
	M21	41.5	-	110.4	68.9	-			
					155		1.171	55.81	74
R057	M26	41.4	-	115.4	74	-			
	M47	42.3	-	107.3	65	-			
					139		1.050	60.37	80
R052	M73	39.7	-	123.5	83.8	-			
	M13	41.2	-	114.7	73.5	-			
					157.3		1.188	55.16	73
2nd batch									
R054	M48	40.8	-	106.8	66	-			
	M29	41.4	-	117	75.6	-			
					141.6		1.070	59.63	79
R053	M6	41.3	-	112.4	71.1	-			
	M3	41.7	-	109.1	67.4	-			
					138.5		1.046	60.52	80
R056	M80	38.8	-	115.1	76.3	-			
	M45	41.1	-	122.2	81.1	-			
					157.4		1.189	55.13	73
3rd batch									
R051	M21	41.5	163	135.2	93.7				
	M45	41.1	135	113	71.9				
					165.6	30.07	1.251	52.79	70
R050	M26	41.4	141.9	117.1	75.7				
	M47	42.3	125.2	105.9	63.6				
					139.3	31.66	1.052	60.29	80
R059	M6	41.3	136.6	113.5	72.2				
	M48	40.8	155.1	127.3	86.5				
					158.7	32.07	1.199	54.76	72

1st batch	tin No	Tin (g)	tin + wet	tin+dry	dried soil	WC	BD g/cm3	Pore volume (%)	Pore Volume (ml)
4th batch									
R056	M73	39.7	157.1	131.2	91.5				
	M80	38.8	141.5	118.8	80				
					171.5	28.34	1.296	51.11	68
R055	M13	41.2	131.9	109.6	68.4				
	M41	41.2	135.9	111.5	70.3				
					138.7	33.67	1.048	60.46	80
R057	M3	41.7	155.3	114.5	72.8				
	M29	41.5	139.6	117.9	76.4				
					149.2	41.89	1.127	57.47	76

Appendix H:

Vertical swelling of soil cores during the draining and wetting processes

Appendix H: Vertical swelling of soil cores during the draining and wetting processes (mm)

Ring No	Points	Initial (mm)	Saturation	-1 kPa	-3 kPa	-5 kPa	-7 kPa	-10 kPa	-7 kPa	-5 kPa	-3 kPa	-1 kPa	0 kPa
R037	A	28.5	1	-0.5	0	-0.5	0	0	0	0	0	0.5	0
	B	30	0	0	-0.5	0	0	0	0	0.5	0	0	0
	C	30	0	-0.5	0	0	0	0	0	0.5	0	0	0
R033	A	30	0.5	0	-0.5	0	0	0	0	0	0	0	0
	B	29.5	1	-0.5	-0.5	0.5	-0.5	0	0	0	0	0	0
	C	30	0	0	0	0	0	0	0	0	0	0	0
R036	A	29.9	0.1	0	0	-0.5	0	0	0	0.5	0	-0.5	0
	B	29	0	0	-0.5	0	0	0	0	0	0	0	0.5
	C	28.5	0.5	0	-0.5	0	0	0	0	0.5	0	0	0
R041	A	30	0.5	-0.5	0	0	0	0	0	-0.5	0	0.5	0
	B	29	1	0	-0.5	0	0	0	0	0	0	0.5	0
	C	30	0	-0.5	0	0	-0.5	0	0	0.5	0	0.5	0
R044	A	28.5	0.5	0	-0.5	0	0	0	0	-0.5	0	1	0
	B	28.5	1	-0.5	-0.5	0	0	0	0	-1	0	1.5	0
	C	28.5	0.5	0.5	-1	-0.5	0	0	0	0	0	1	0
R030	A	28.5	1.5	-1	0	0	-0.5	0	0	-1	0	1	0
	B	29.5	1	-0.5	0	0	-1	0	0	0	0	0.5	0
	C	29	1	0	-0.5	0	-0.05	0	0	0.05	0	0.5	0
R039	A	30	1	0	-1	0	0	0	0	0.5	0	0.5	0
	B	32	1	0	-1.5	0	0.5	0	0	0.5	0	0.5	0
	C	29.5	1.5	-1	-0.5	0	0	0	0	0	0	0.2	0.3
R040	A	30	0	0	-0.5	0	0	0	0	-0.5	0	1	0
	B	29.5	0	0.5	-0.5	0	0	0	0	0	0	0	0
	C	29.5	0	-0.5	0	0	0	0	0	1	0	-0.5	0
R032	A	30	0	0	-0.5	0	0	0	0	0	0	0	0
	B	30.5	0.5	-0.5	0	0	0	0	0	0	0	0.5	0
	C	30	0	-0.5	0	0	-0.5	0	0	0.5	0	0.5	0

Average = 0.022 ± 0.023 mm

Appendix I:

Properties of tap water and laundry water, and their leachate

Table I1: Properties of tap water and laundry water used in the experiment

TW (3 replicates)	Calcium	Potassium	Magnesium	Sodium	SAR	pH	EC, µS/cm
	mg/l						
A	21	4.7	16	34			
B	21	4.6	16	34			
C	21	4.6	16	34			
	meq/l						
A	1.048	0.120	1.316	1.479	1.36	6.7	384
B	1.048	0.118	1.316	1.479	1.36	6.7	383
C	1.048	0.118	1.316	1.479	1.36	6.68	398
				Mean	**1.36**	**6.69**	**388.33**
				SE (n = 3)	**0.00**	**0.01**	**4.84**
LW	Calcium	Potassium	Magnesium	Sodium	SAR	pH	EC, µS/cm
mg/L	2.1	5.7	4	132		9.22	754
meq/L	0.105	0.146	0.329	5.742	12.33	9.21	753
						9.21	748
					Mean	**9.21**	**751.67**
					SE (n = 3)	**0.003**	**1.86**

Table I2: Properties of the tap water and laundry water leachate

Tap Water Leachate							
Core treatments	Calcium	Potassium	Magnesium	Sodium	**SAR**	**pH**	**µS/cm**
Field	0.898	0.043	0.905	1.218	1.283	6.57	314
	0.998	0.105	0.987	1.261	1.266	5.93	335
Average SAR, pH and EC for compacted core treatment =					**1.274**	**6.25**	**324.5**
Loose	0.798	0.066	0.740	1.261	1.438	5.98	312
	0.898	0.072	0.905	1.305	1.374	5.71	313
Average SAR, pH and EC for compacted core treatment =					**1.406**	**5.845**	**312.5**
Compacted	0.898	0.069	0.814	0.913	0.987	6.09	298
	0.898	0.074	0.905	0.957	1.008	5.99	291
Average SAR, pH and EC for compacted core treatment =					**0.997**	**6.04**	**294.5**
Mean ± SE from all three soil core treatments (n = 6)					**1.2 ± 0.08**	**6.05 ± 0.12**	**310.5 ± 6.21**
Laundry Water Leachate							
Field	0.848	0.033	0.905	2.827	3.020	6.76	458
	1.198	0.107	1.152	1.914	1.766	6.26	415
Average SAR, pH and EC for field treatment =					**2.393**	**6.51**	**436.5**
Loose	1.148	0.084	1.152	1.696	1.582	6.47	418
	1.198	0.097	1.234	1.783	1.617	5.99	414
Average SAR, pH and EC for loose core treatment =					**1.600**	**6.23**	**416**
Compacted	1.148	0.084	1.070	1.435	1.363	6.09	408
	0.998	0.079	0.987	1.348	1.353	6.67	359
Average SAR, pH and EC for compacted core treatment =					**1.358**	**6.38**	**383.5**
Mean ± SE from all three soil core treatments (n = 6)					**1.8 ± 0.26**	**6.37 ± 0.13**	**412 ± 12.90**